Fermilab Booster Space Charge Study

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December 12, 2002
Mid-West Accelerator Physics Collaboration, Indiana Univ.

http://www-bd.fnal.gov/pdriver/booster/

Motivation

- This is one of the recommendations of the DOE Review panel
- Although the Booster looks fine for Run2, its beam intensity (protons per second) is only 1/8 of the MiniBooNE goal

Plan

- Simulations
  - To make ORBIT a production code
  - To compare ORBIT with ESME for longitudinal space charge
  - To compare ORBIT with SYNERGIA (IMPACT)
- Booster modeling using MAD
  - To continue the improvement of the Booster lattice model, which will include sextupoles, correctors, alignment errors, magnet field errors, orbit bump, doglegs, and impedance
- Booster magnet measurement
  - To continue the flat coil measurement at the E4R, in particular for body and ends sextupole component

- Booster beam study
  - A study plan has been drafted
  - Will be coordinated by the Booster Dept
  - Measurements to be completed in 6 months
- Collaborations
  - SNS/ORNL (Jeff Holmes) on ORBIT
  - Indiana University (S.Y. Lee) and ANL (S. Milton) on space charge study
  - CERN (B. Dehning) and BNL (R. Connolly) on IPM

How this study will help improve the Booster performance

- To build a useful Booster model
- To understand emittance dilution and beam loss, and the role of the space charge and other associated effects (e.g., electron cloud)
- To evaluate possible changes in machine operation, e.g.,
  - The waveform of the injection bump
  - Tune ramp curve
  - RF voltage curve
  - Tune split, etc.
- To get insight of what happens during transition crossing
- To investigate and experiment
  - Inductive inserts (D. Wildman)
  - Transverse quadrupole mode pickup and damper (A. Jansson)
  - Electron beam compensation (V. Shiltsev)
  - Other proposals

Fermilab Booster Parameters (December 5, 2002)

Circumference (m)	474.2
Average machine radius (m)	75.47
Injection/Extraction kinetic energy (GeV)	0.4, 8
Repetition rate (Hz)	15
RF frequency (MHz)	37.87 – 52.81
Harmonic number	84
Protons per bunch	6×10^{10}
Protons per cycle	5×10^{12}
Protons per second*	2.5×10^{13}
Protons per hour*	9×10^{16}
Average beam current* (μA)	4
Average beam power* (kW)	32
Lattice	FOFODODO
Super-periodicity	24
Cell length (m)	19.758
Length of combined function magnet (m)	2.889612
Magnet per cell	4
Magnet total	96
Number of straight sections	24 Long, 24 Short, 48 Mini
Length of each straight section (m)	6(Long), 1.2(Short), .5 (Mini)
Max/Min β_x (m)	33.67 (Short)/6.12 (Long)
Max/Min β_y (m)	20.46 (Long)/5.27 (Short)
Max/Min D_x (m)	3.19 (Long)/1.84 (Short)
Phase advance per cell φ_x, φ_y (degree)	100.5, 102
Horizontal, vertical tune ν_x, ν_y	6.7, 6.8
Natural chromaticity ξ_x, ξ_y	-9.2, -7.0
Transition γ_t	5.45
Transition momentum (GeV/c)	5.03
Transition crossing moment (ms)	17
β at injection, extraction	0.713, 0.994
γ at injection, extraction	1.426, 9.526
$\|\eta\|$ at injection, extraction	0.458, 0.0227
Revolution frequency at injection, extraction (kHz)	450.8, 628.7
Revolution time at injection, extraction (μs)	2.22, 1.59
Injection turns (typical)	11
Injection time (typical, μs)	24.4
Injection linac peak current (typical, mA)	40
Maximum Laslett tune shift	0.4
Normalized transverse emittance ε_N (95%, mm-mrad)	$12\ \pi$
Longitudinal emittance (95%, eV-s)	0.1

* MiniBooNE continuous operation at 5 Hz.

Booster Beam Study Plan

(Revised, 12/09/02)

Schedule: A and B to be implemented in the next 6 months; C to be determined.

Simulations: ORBIT – Francois, Leo, Weiren
SYNERGIA – Panagiotis, Jim (A.)
MAD – Sasha, Norm, Weiren

Beam study: (see names in each item)

A. Measurements:
   a) Parasitic measurements:
      1. Longitudinal emittance and profile:
         - At injection:
            - Panagiotis and Jim (A.) measured the first 8 turns using the 6-GHz wall current monitor in L18. Data are posted on the web.
            - In the 400 MeV line upstream from the Debuncher, there is a "Griffin" pickup (made of striplines) that can be used for this measurement. But one may need to add 3 more cables to it. Ray will do it.
         - At top energy:
            - In the ring: Ray, Bill (P.), Francois, Weiren.
            - In the MI-8 line: There is also a 6-GHz pickup. Need help from Bill (P.) to use it.
         - Turn-by-turn:
            - To be planned when simulation results (ORBIT and/or SYNERGIA) are available.
      2. Transverse emittance and profile:
         - At injection:

    - Panagiotis and Jim (A.) measured the first 30 turns using the flying beam method. (The injection orbit bump pulse length limits the measurable number of turns.)
    - This is for horizontal plane only.
    - They also have the data of the 400 MeV line using multi-wire.
    - Ray has tried to use the collimator to measure the vertical plane.
    - Data will be available on the web.
  - At top energy:
    - Panagiotis and Jim (A.) are measuring it using IPM.
    - They also have the data of the MI-8 line using multi-wire.
    - Data will be available on the web.
  - IPM calibration:
    - By comparing the IPM raw data with the multi-wire data, Panagiotis and Jim (A.) found the IPM data is about 30% larger at both injection and top energy.
  - Turn-by-turn:
    - To be planned when simulation results (ORBIT and/or SYNERGIA) are available.
3. Beam position:
  - At injection:
    - The regular BPM cannot take data until after about 50 turns.
    - One can try the IPM in the first 50 turns.
    - Three BPMs - S24, DSL1 and S1 - can measure the orbit in the first 50 turns, provided that only 1-turn injection is used. (They have the 200 MHz electronics.)
    - Jim (L.), Ray, Francois, Weiren.

- Turn-by-turn
    - Data to be compared with simulation (MAD), which includes alignment and field errors.

4. Tune during ramp:
    - Ray did it using a vertical pinger fired at 2 kHz, i.e., every 0.5 ms. (The horizontal tune is also measurable due to coupling.)
    - Data will be posted on the web and compared with simulation (ORBIT), which includes space charge tune shift.
5. Chromaticity during ramp:
    - Ray did it also with the vertical pinger.
    - Data will be posted on the web and compared with simulation (MAD), which includes magnet sextupoles (measured by the TD) and correction sextupoles.
6. Quadrupole moment:
    - Jim (L.) used the BPM in L4 and S4 for this measurement, because the cables of the two BPM were measured to the nanosecond accuracy.
    - Measurement will be redone and data need to be understood.
    - Jim (L.), Francois, Weiren, Andreas.
7. Emittance dilution due to foil scattering:
    - Carol did it for the 200 MeV linac and 200 $\mu g/cm^2$ foil and found 0.5% emittance dilution per hit.
    - Will redo it for the 400 MeV linac and 540 $\mu g/cm^2$ foil.
    - Jim (L.), Carol, Francois, Weiren.

b) <u>Dedicated measurements:</u>
Requests will be submitted to Eric, coordinator of the Booster study. There are two possibilities: one is during shot setup when the pbar production is on hold; another is when some

machine is down. But one may also request specific Booster study time when necessary.

1. Dependence of the above measurements on beam intensity and working point.
2. Varying tune ramp curve:
    - To be planned when simulation results (ORBIT) are available.
3. Varying chromaticity ramp curve:
    - To be planned when simulation results (MAD) are available.
4. Machine acceptance:
    - Longitudinal:
        - Linac beam energy can be varied and measured (by an energy meter) for this measurement.
        - 400 MeV line needs to be retuned.
        - Milorad, Elliott, Francois, Weiren.
    - Transverse:
        - There is an aperture scan program available based on 3-bump method.
        - Prefer to use "pencil beam" (in physical space by scraping) for this measurement, which can be obtained by scraping the beam in the 400 MeV line.
        - Jim (L.), Francois, Weiren.
5. Lattice function:
    - Shekhar (S.) did this but data got lost.
    - Milorad will try to find the program and redo it.
6. Stopband using "pencil beam" (in tune space):
    - Chuck (A.) did this in the '80s and also last year. It needs to be redone.
    - Eric has a program for coupling correction.
    - Chuck (A.), Ray, Eric, Francois, Weiren.

B. <u>Experiments:</u>

a) Inductive inserts:
  - Dave (W.) has made 7 modules, 1-m long each.
  - Installation location and date to be decided.
  - Before installation: To measure the module impedance (Re and Im) as a function of frequency up to 200 MHz.
  - After installation: To measure bunch spectrum and longitudinal quadrupole oscillation frequency.
  - Dave (W.), Ray, Weiren.

b) Tune split:
  - To be planned when simulation results (ORBIT) are available.

c) Injection orbit bump waveform:
  - To be planned when simulation results (MAD) are available.
  - Jim (L.) will provide current waveform and magnet field data.

C. <u>Hardware development:</u>

a) IPM modification:
  - First step will be to relocate MI IPM clearing field power supply (30 kV) to the Booster.
  - In the meantime, to start the design of converting IPM to electron collecting. The key element is permanent magnets, of which we probably need six (two large aperture ones for the IPMs, four small aperture ones for correction).
  - Jim (Z.), Stephen (P.), Weiren.

b) Transverse quadrupole mode pickup :
  - First we will use the L4/S4 BPMs (see item A a) 6).
  - In the meantime, to have a feasibility study of fabricating an inductive pickup similar to the one at the CERN PS (to investigate the purpose, requirement, manpower, budget and schedule).
  - Andreas, Jim (L.), Francois, Weiren.

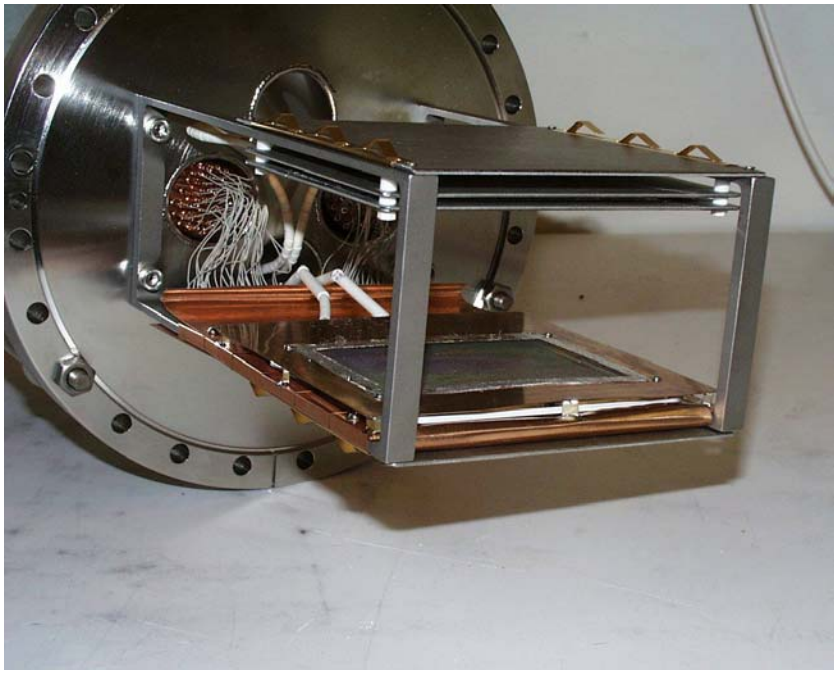


Figure 1. Complete, MCP.
This is the original transducer head which is inserted into a side port of a 4" x 6" rectangular chamber. This design has been susceptible to rf pick up from the beam, readiation spray and background electrons.

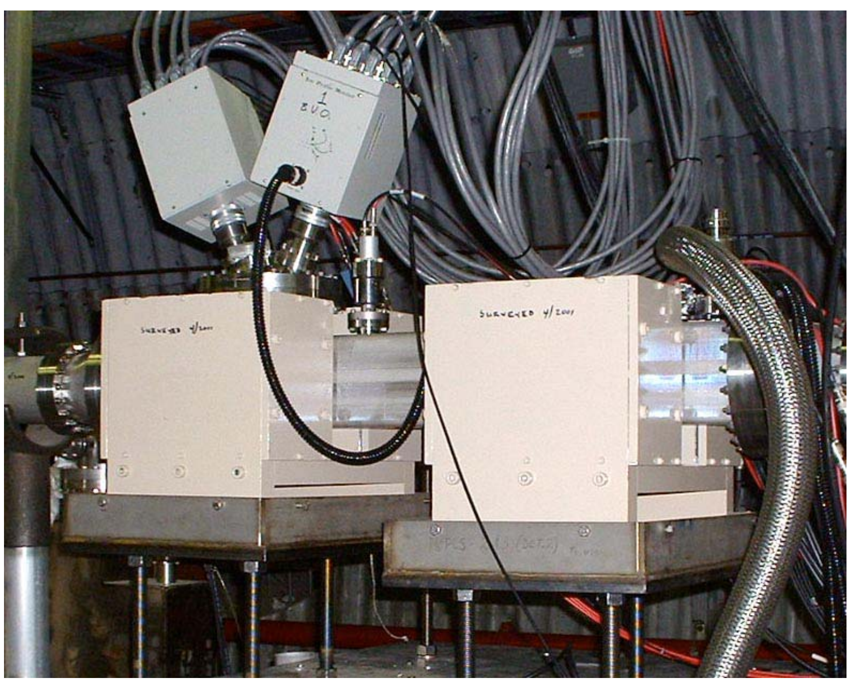


Figure 2. Vertical IPM.
One IPM in the tunnel. The amplifiers are attached directly to the mounting flange.

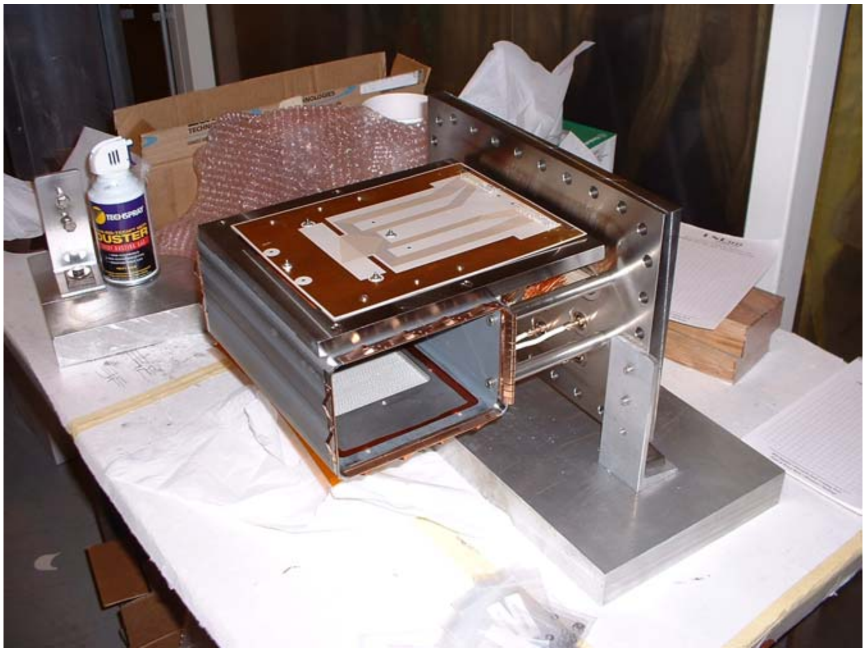
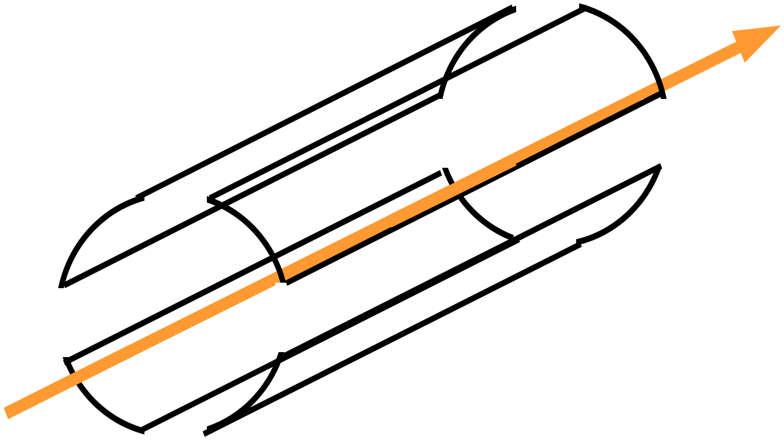


Figure 3. Finished, 1.
The new detector head. The rectangular insert provides an uninterrupted path for image current. The MCP and collector circuit board are outside of the image current path. The sweep electrode is flush with the beam pipe and longer to sweep background electrons from the pipe before they get to the collector.

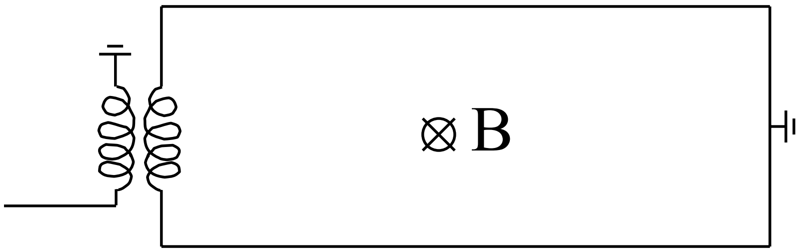
Figure 4. Detector inserted chamber.
An unfinished transducer head being inserted into the vacuum chamber.

Lessons from lab measurements



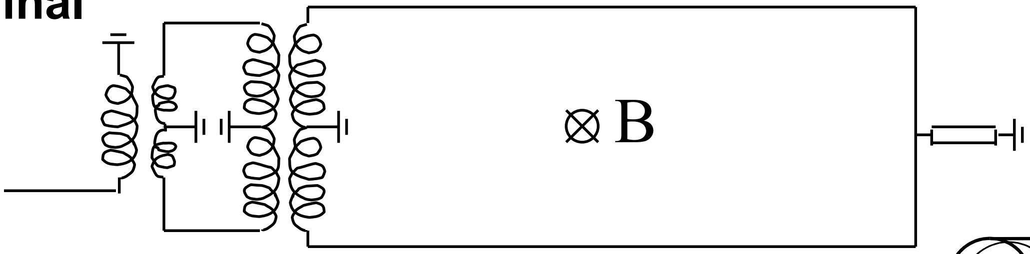
➔ **Initial design of induction loop had problem with resonances.**

Initial design:



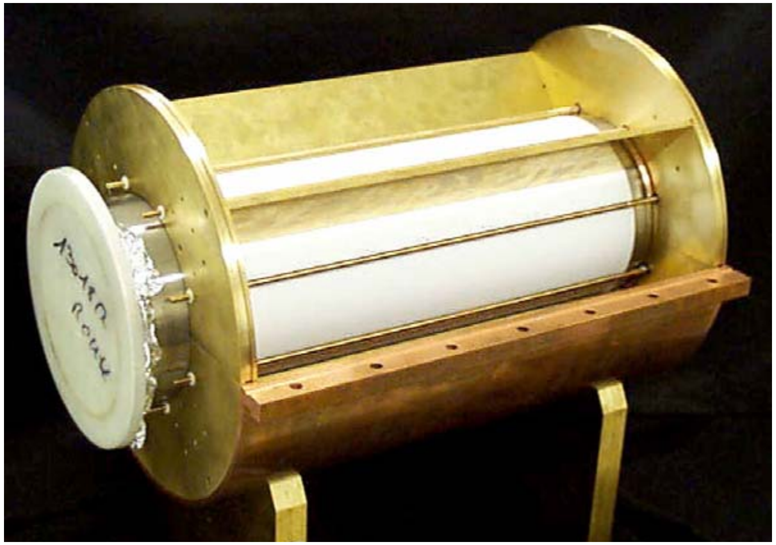
➔ **After some iterations, a design with good common-mode rejection and low longitudinal impedance, was found.**

Final design:



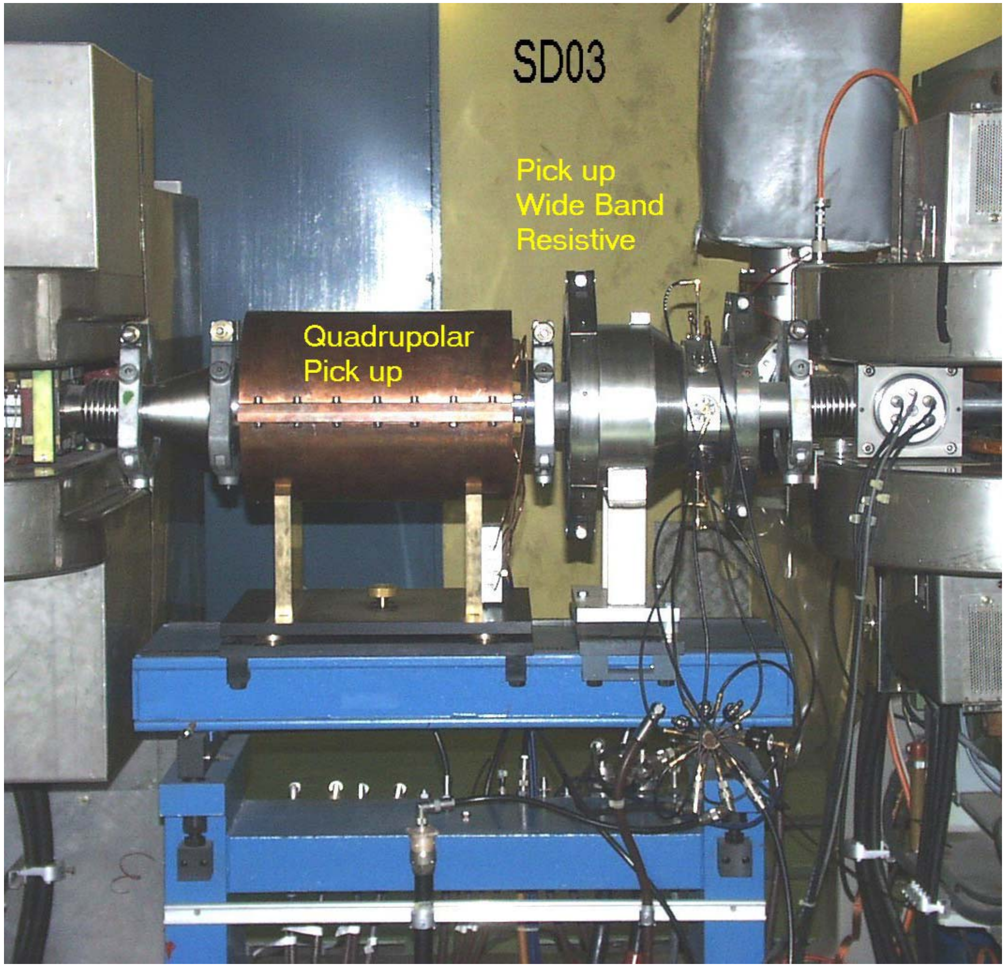
Final pickup parameters

- **Transfer impedance**
  - Sum: 0 Ω
  - Dipole: 1.4 mΩ/mm
  - Quadrupole: 34 μΩ/mm^2
- **Bandwidth**
  - ~70 kHz - 25 MHz
    (limited by hybrid and amplifier)
- **Longitudinal impedance**
  - Z/n < 70 mΩ
- **Dimensions:**
  - Length: 50 cm
  - Aperture: 14.5 cm



Pick-up partly assembled

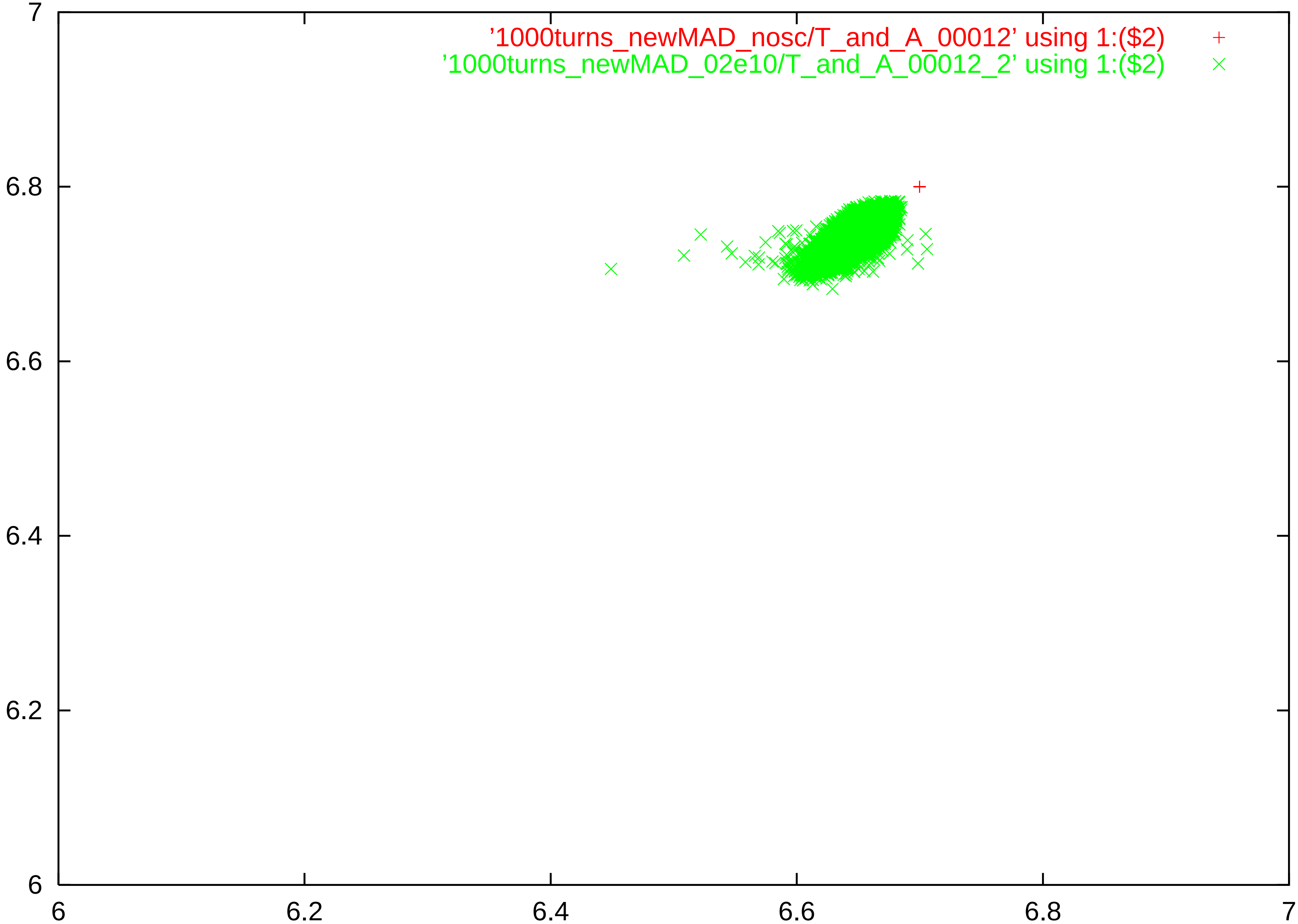
Installation in the PS machine



- ➔ **Two pick-ups in consecutive sections**
- ➔ **"One pick-up per plane"**

	β_h	β_v	D_h
SS 03	**22 m**	**12 m**	**3.2 m**
SS 04	**12 m**	**22 m**	**2.3 m**

- ➔ **Phase advance between pick-ups independent of machine tune**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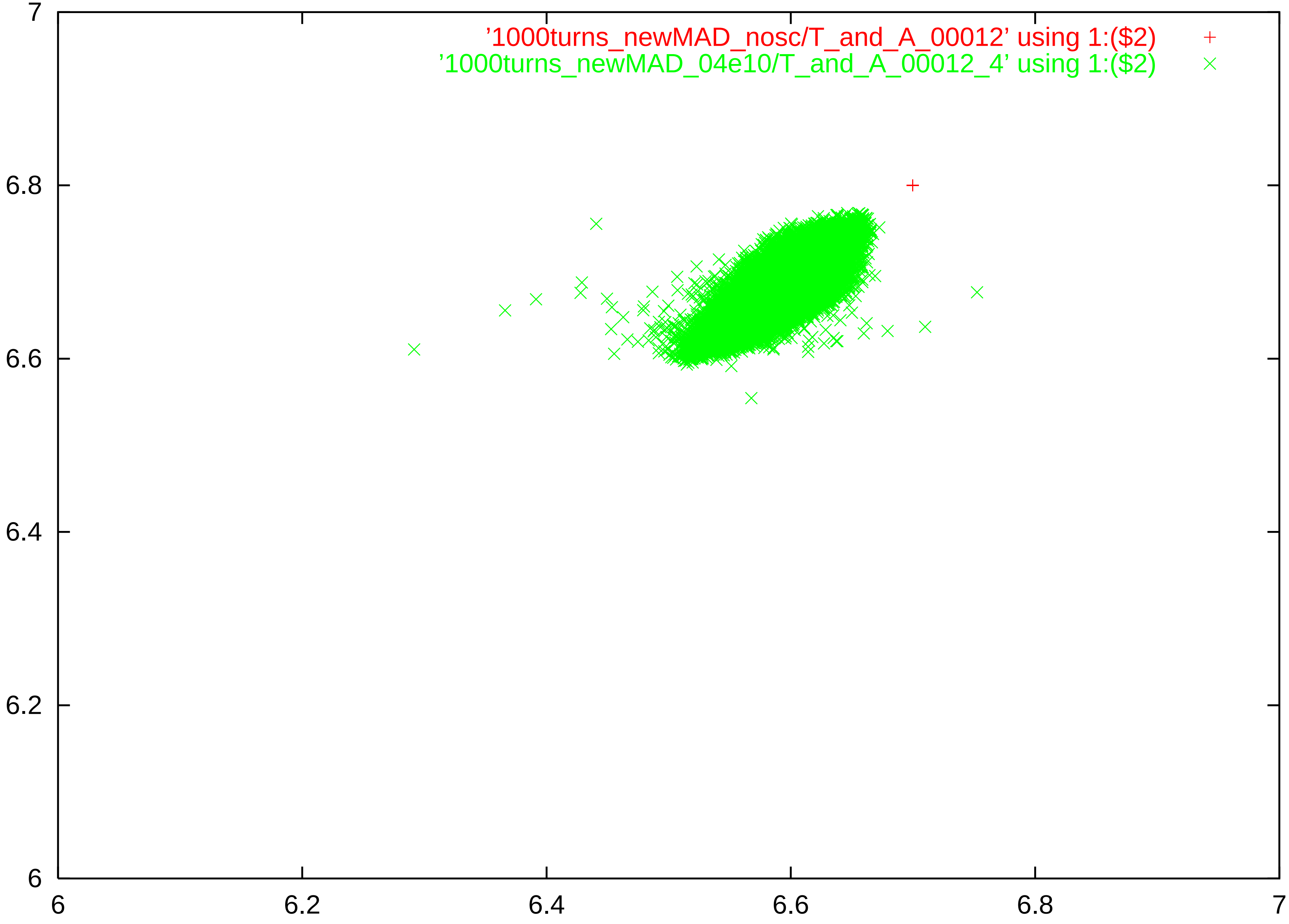
6.8
6.6
6.4
6.2
6
6
6.2
6.4
6.6
6.8
7



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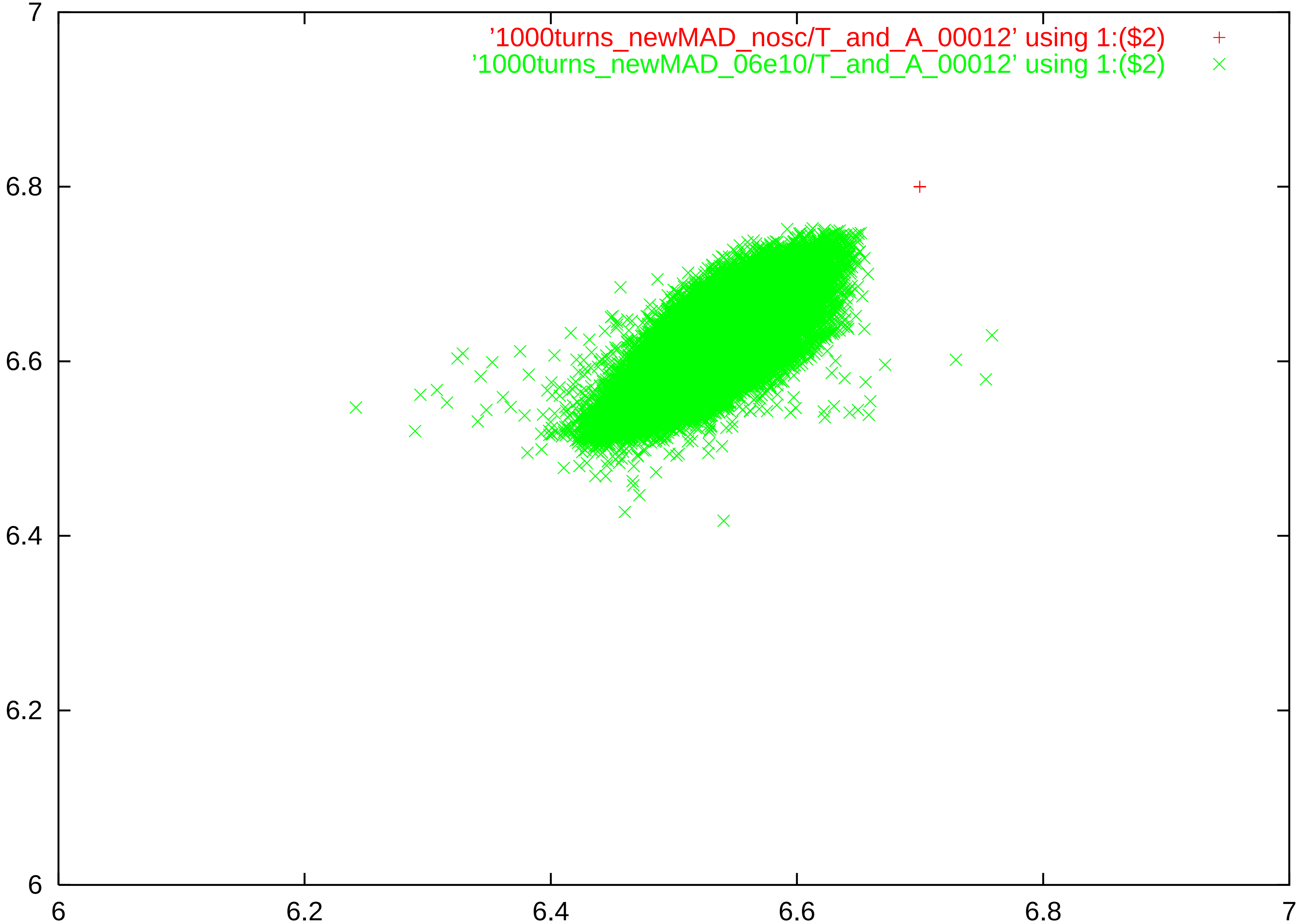
6.8
6.6
6.4
6.2
6
6
6.2
6.4
6.6
6.8
7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6.6
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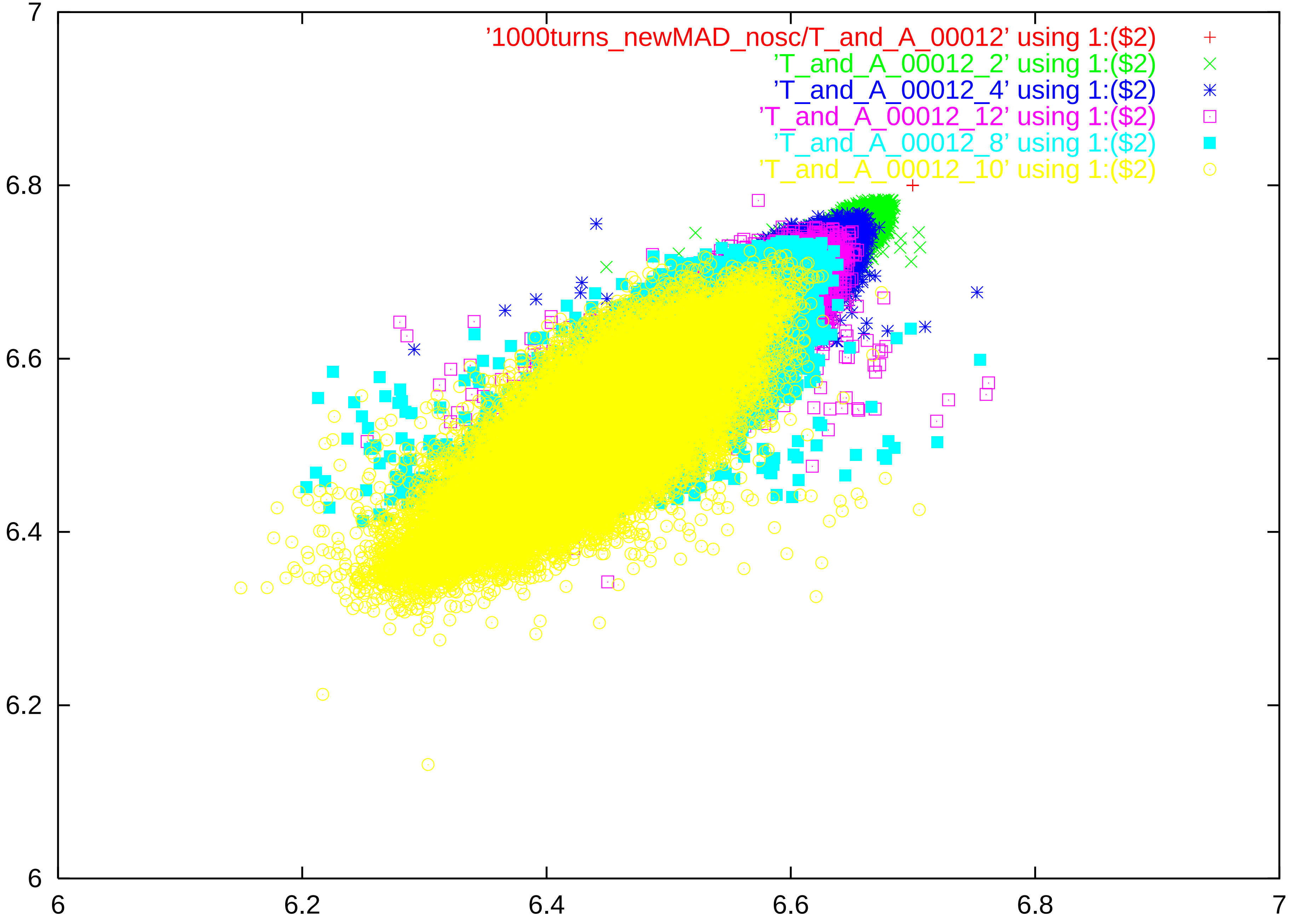
6.6
6.8
7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'T_and_A_00012_4' using 1:($2)
'T_and_A_00012_12' using 1:($2)
'T_and_A_00012_8' using 1:($2)
'T_and_A_00012_10' using 1:($2)
7
6.8
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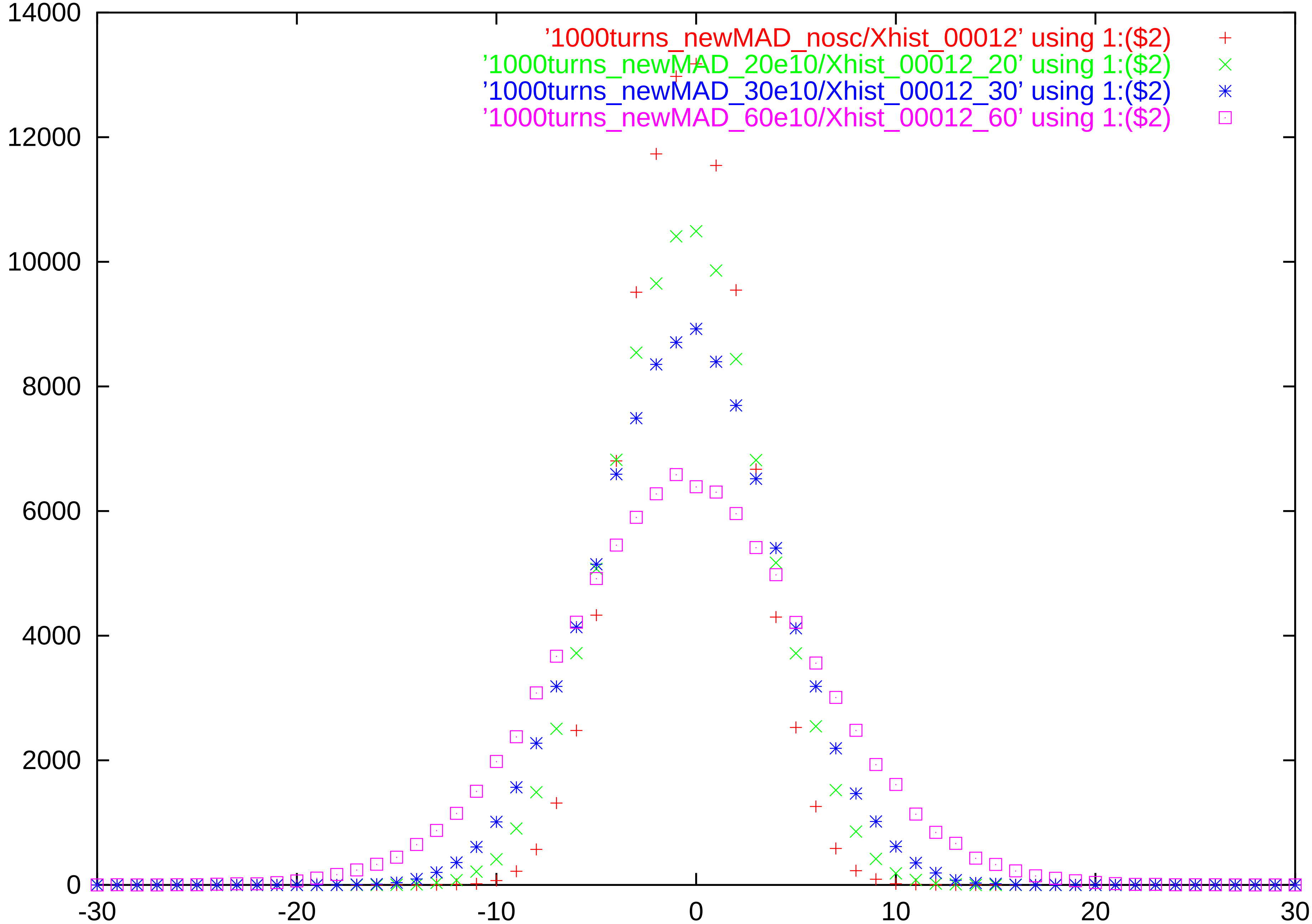
6.6
6.8
7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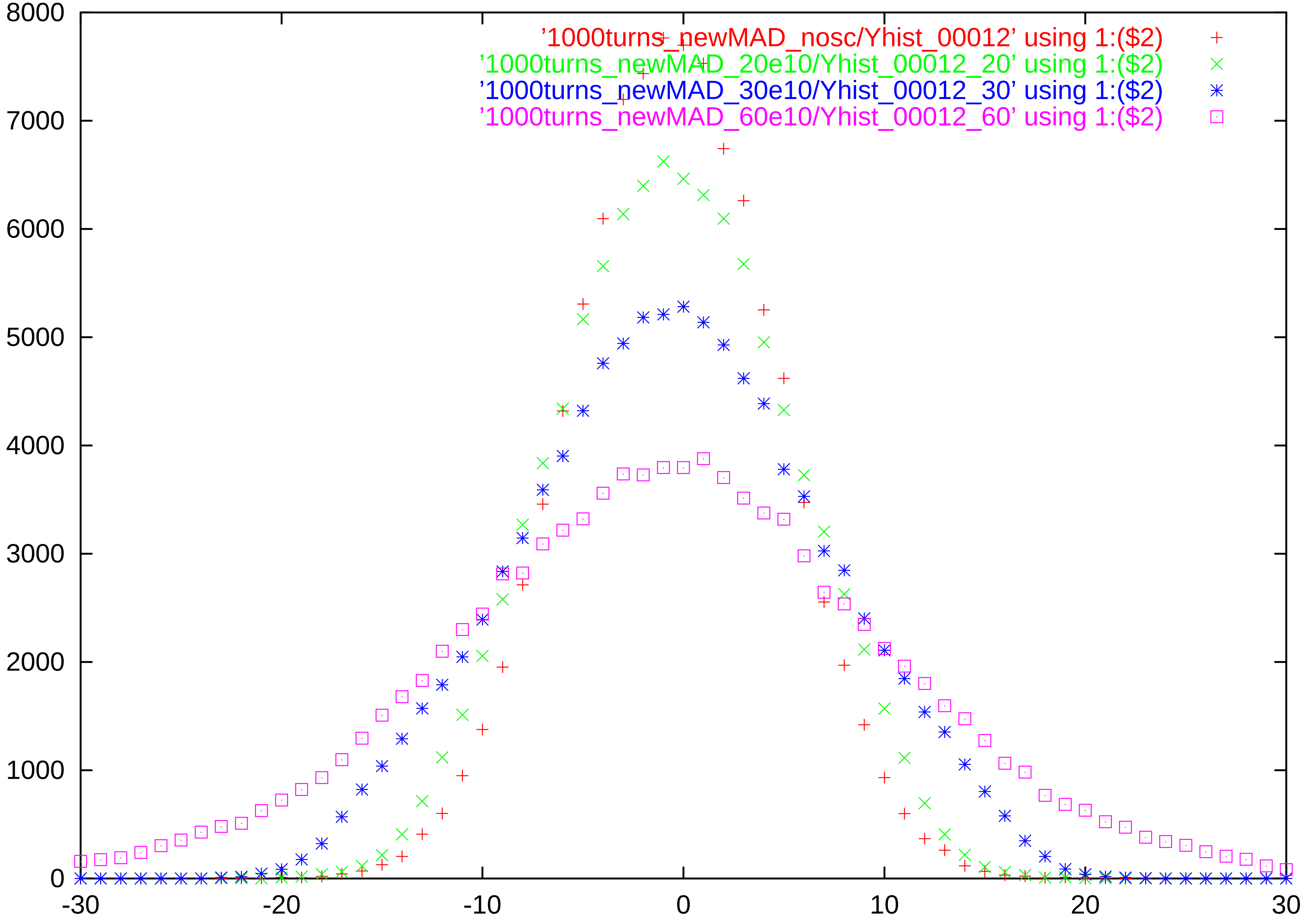
12000
10000
8000
6000
4000
2000
0
-30
-20
-10
0
10
20
30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'1000turns_newMAD_60e10/Yhist_00012_60' using 1:($2)
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6000
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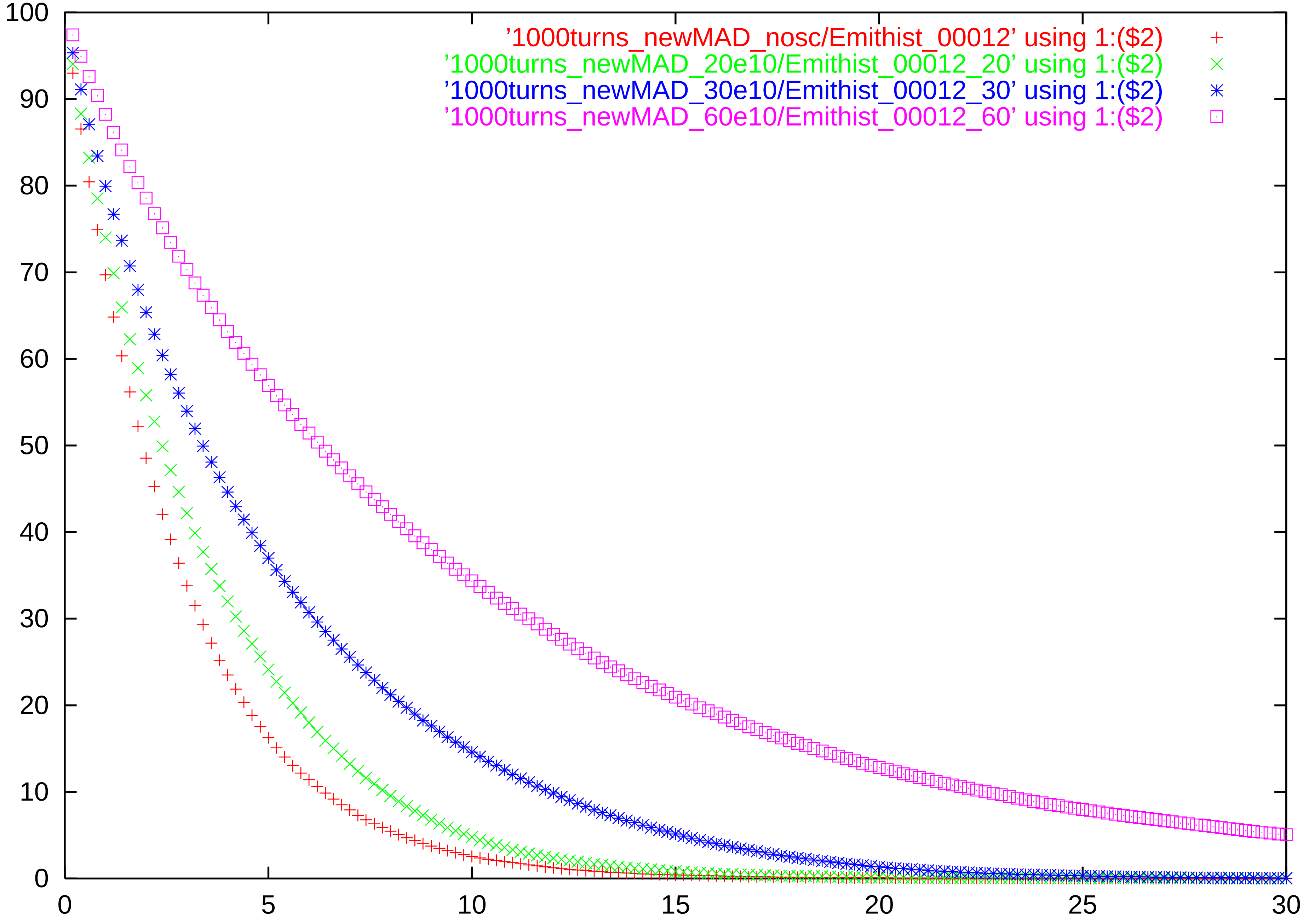
4000
3000
2000
1000
0
-30
-20
-10
0
10
20
30



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'1000turns_newMAD_60e10/Emithist_00012_60' using 1:($2)
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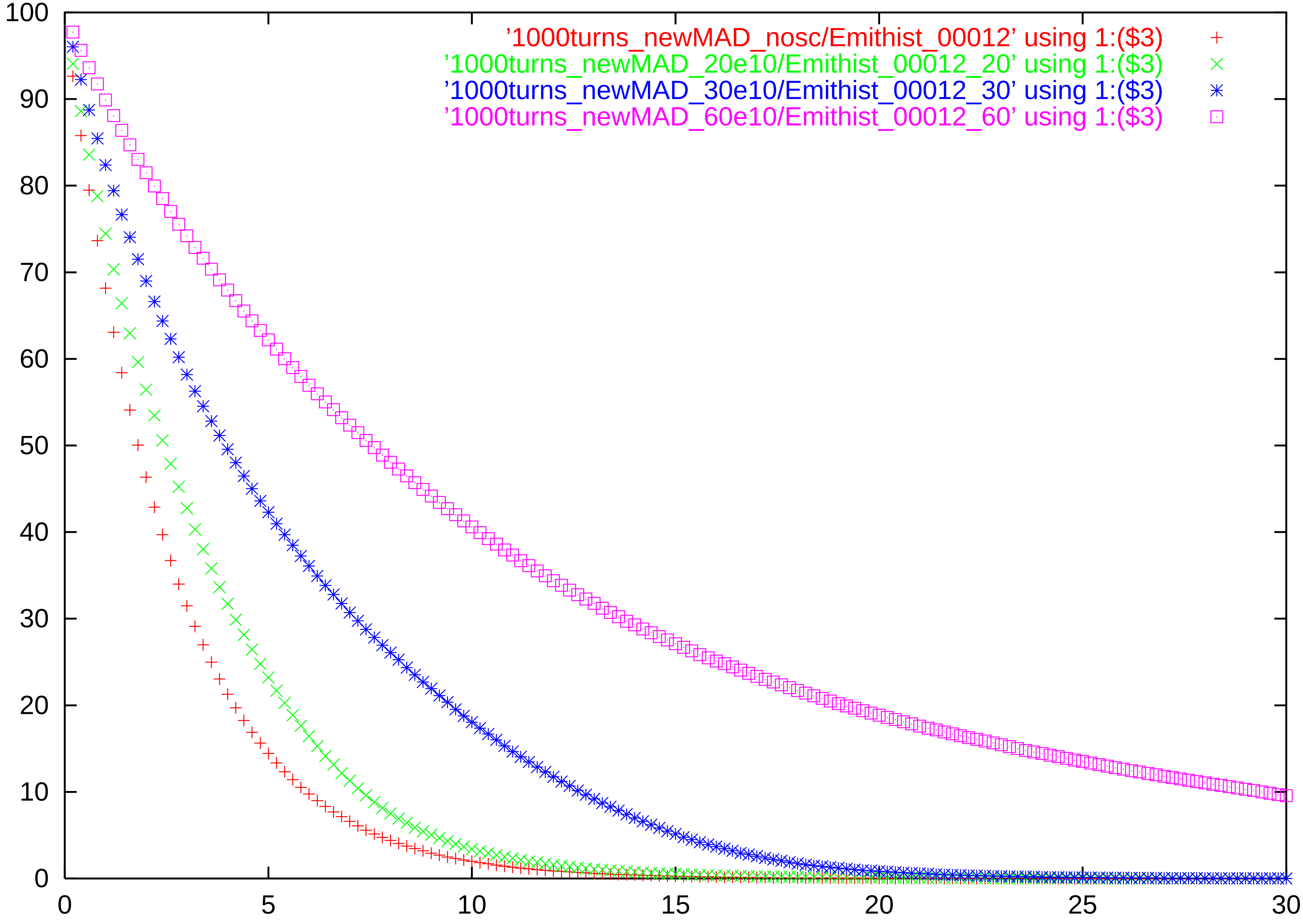
20
30
40
50
60
70
80
90
100
0
5
10
15
20
25
30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'1000turns_newMAD_60e10/Emithist_00012_60' using 1:($3)
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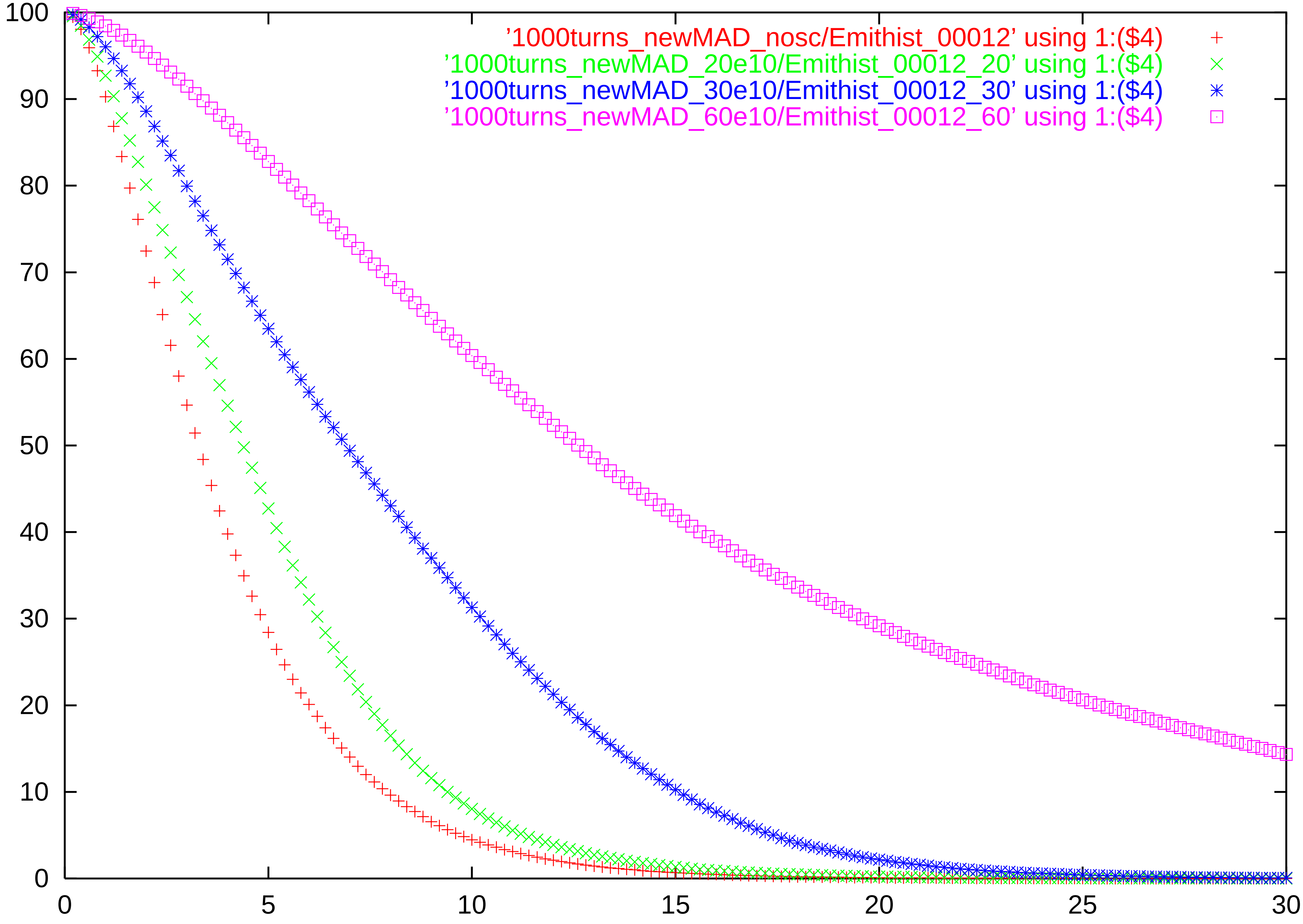
10
20
30
40
50
60
70
80
90
100
0
5
10
15
20
25
30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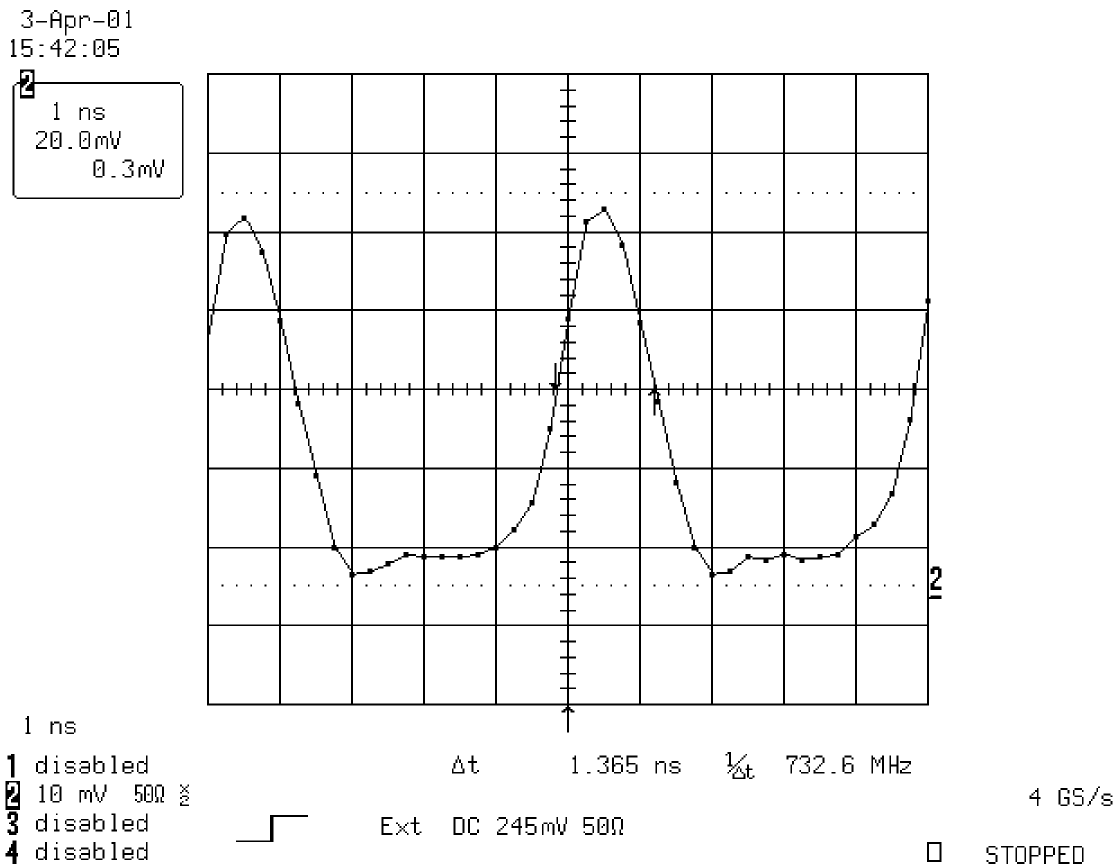
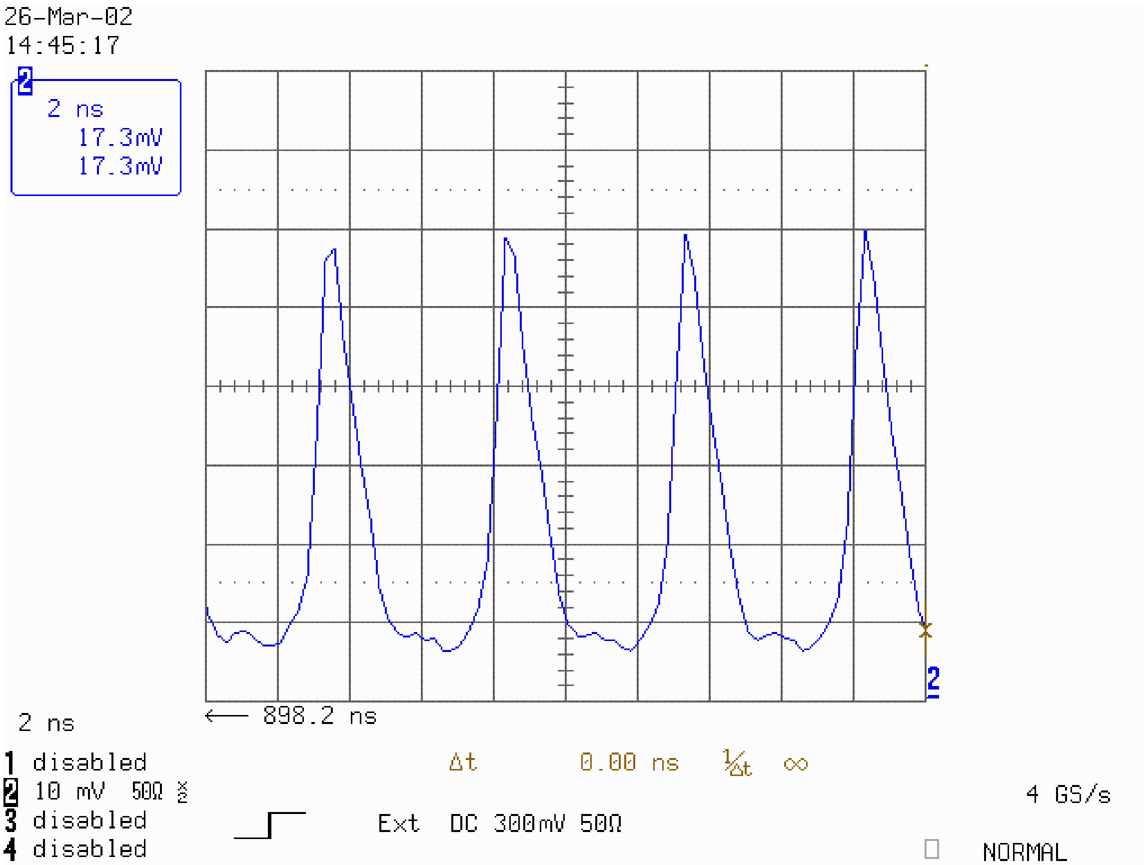
'1000turns_newMAD_30e10/Emithist_00012_30' using 1:($4)
'1000turns_newMAD_60e10/Emithist_00012_60' using 1:($4)
100
90
80
70
60
50
40
30
20
10
0
0
5
10
15
20
25
30

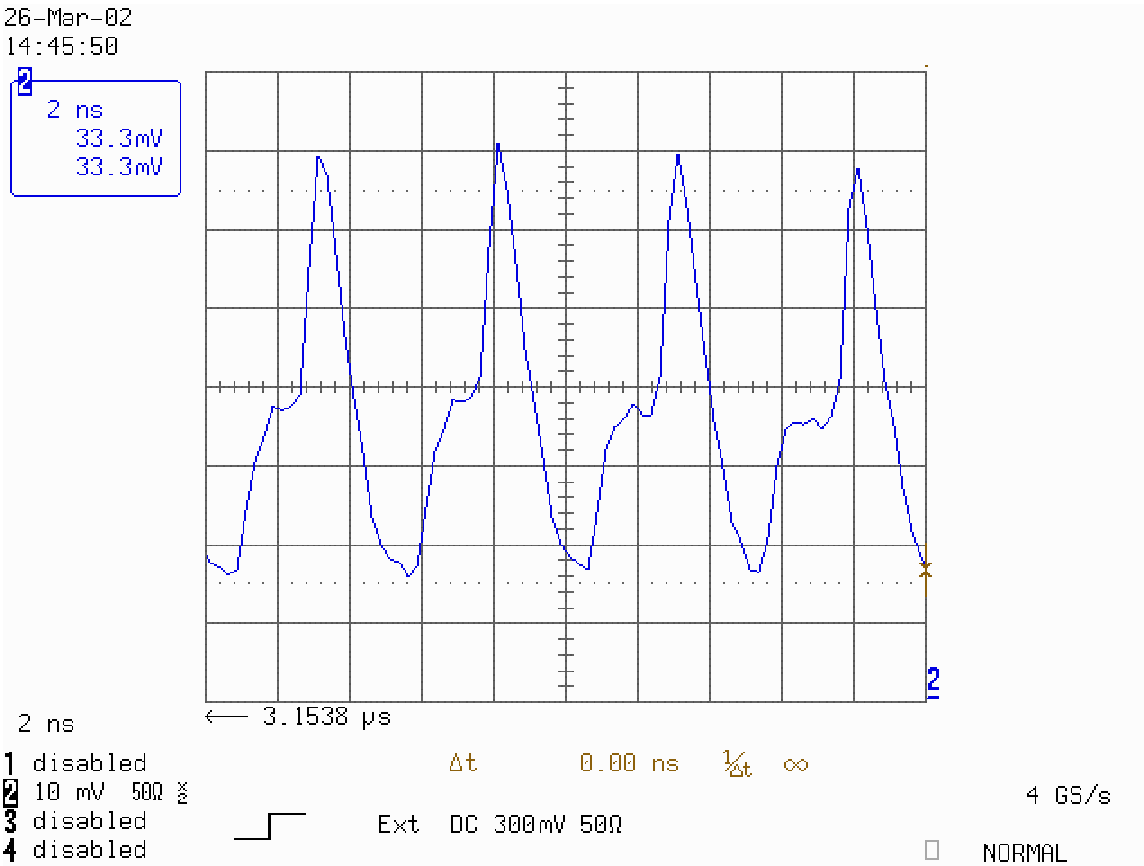
Author: Ray Tomlin
Date: April 3, 2001
Title: Booster 200 MHz bunch length, first turn at L18.



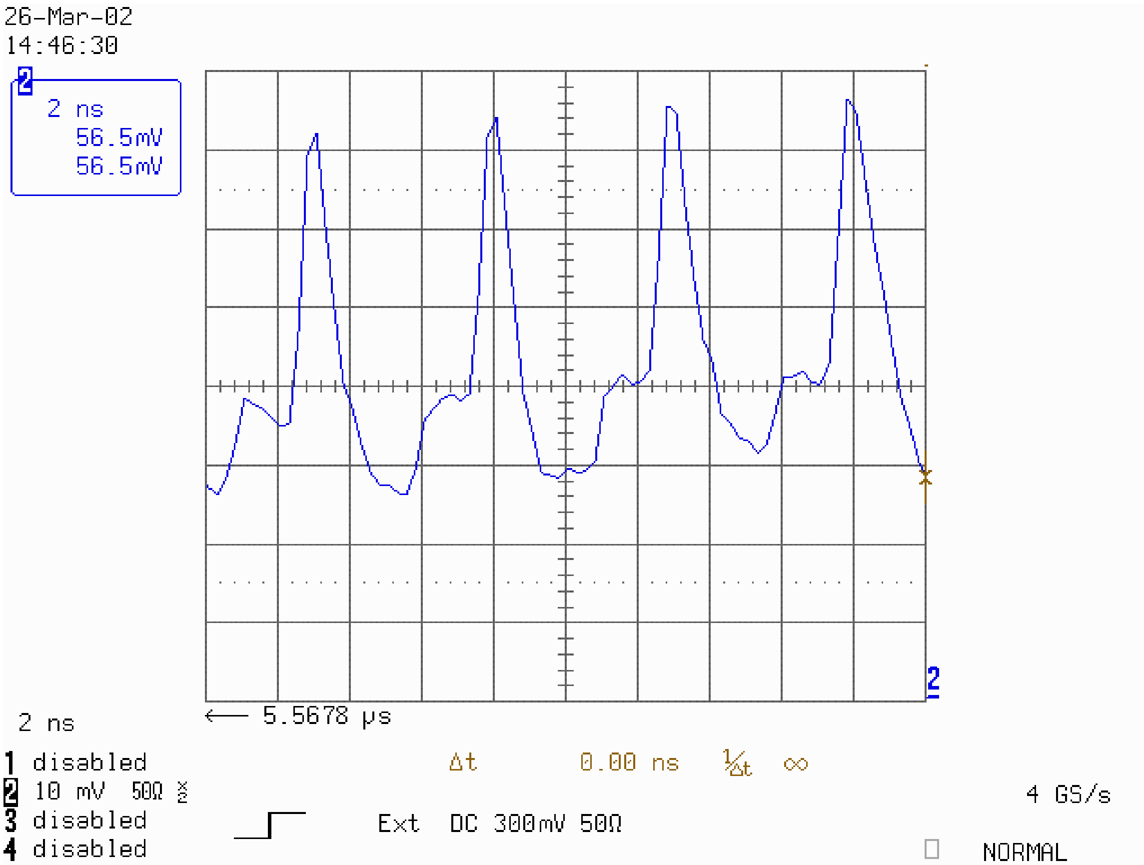
Author: Ray Tomlin
Date: March 26, 2002
Title: Booster 200 MHz bunch length, first pass at L18.



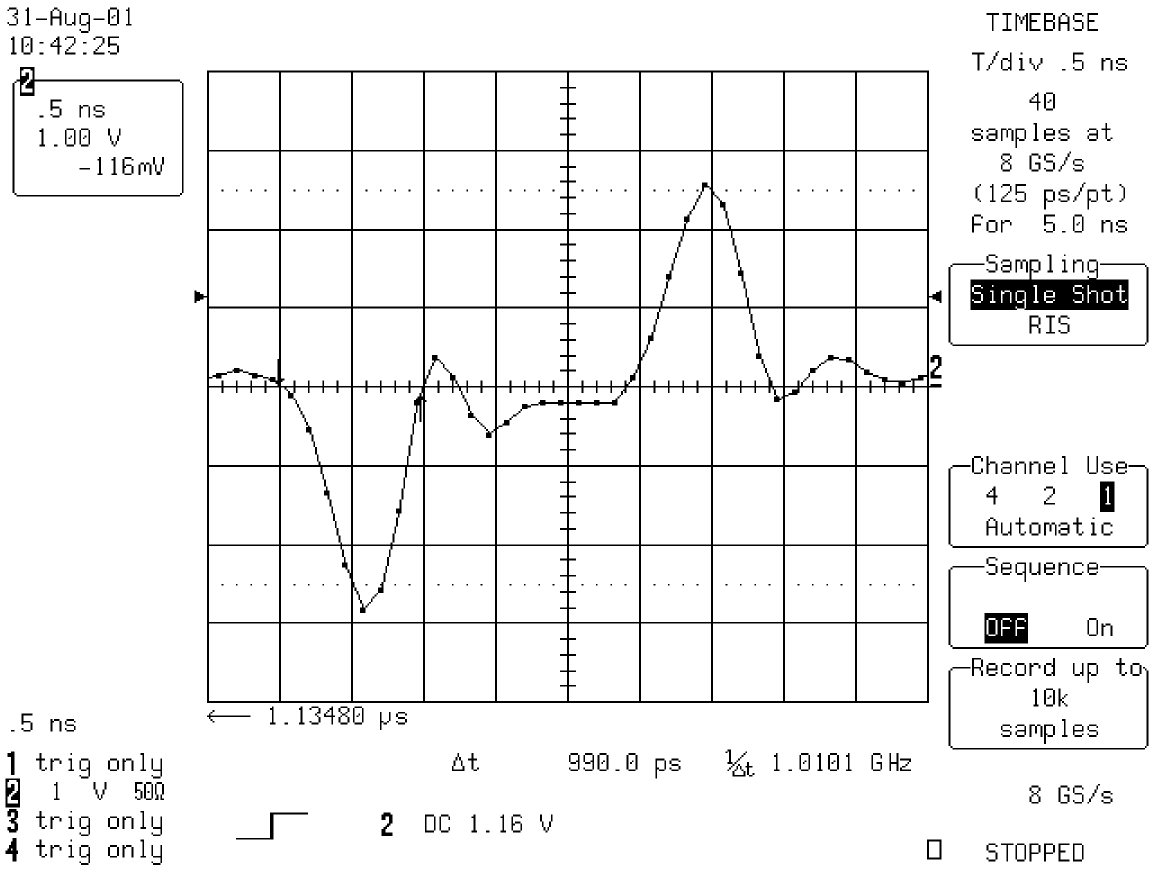
Author: Ray Tomlin
Date: March 26, 2002
Title: Booster 200 MHz bunch length, second pass at L18. (Second-turn injection added on.)



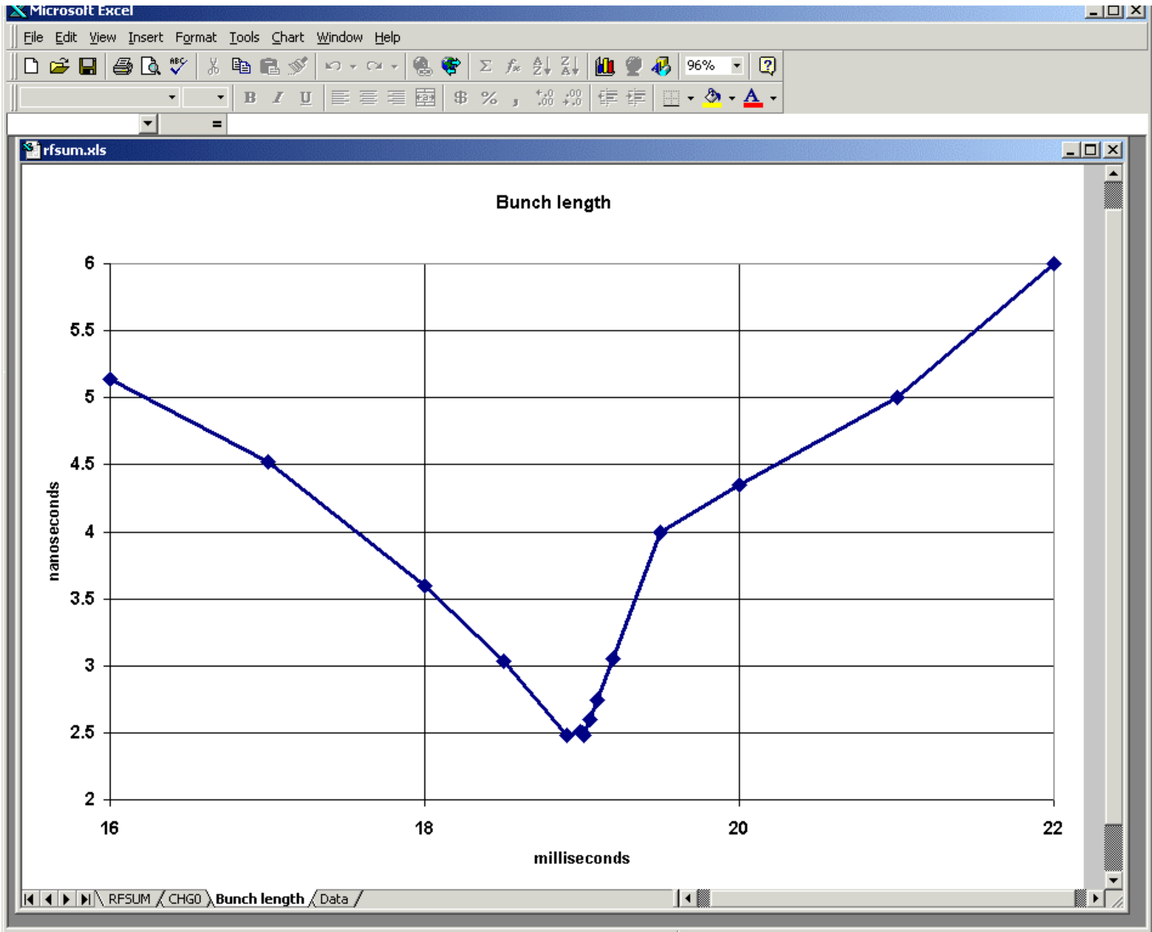
Author: Ray Tomlin
Date: March 26, 2002
Title: Booster 200 MHz bunch length, third pass at L18. (Third-turn injection added on.)



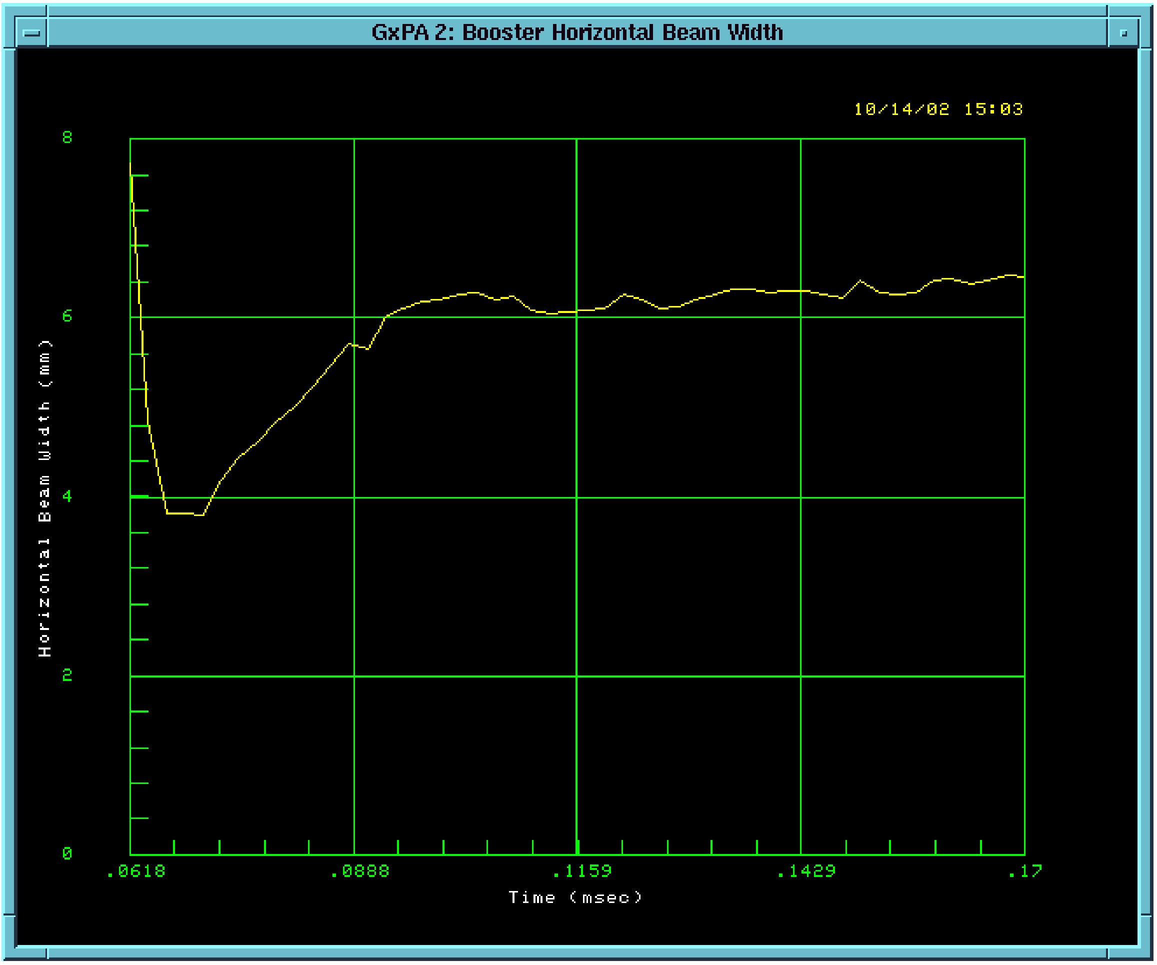
Author: Ray Tomlin
Date: August 31, 2001
Title: Linac 200 MHz bunch length, measured by the Griffin pickup upstream from the debuncher. (Actual bunch length is probably around 625 ps. The LeCroy scope blow it up to 990 ps.)

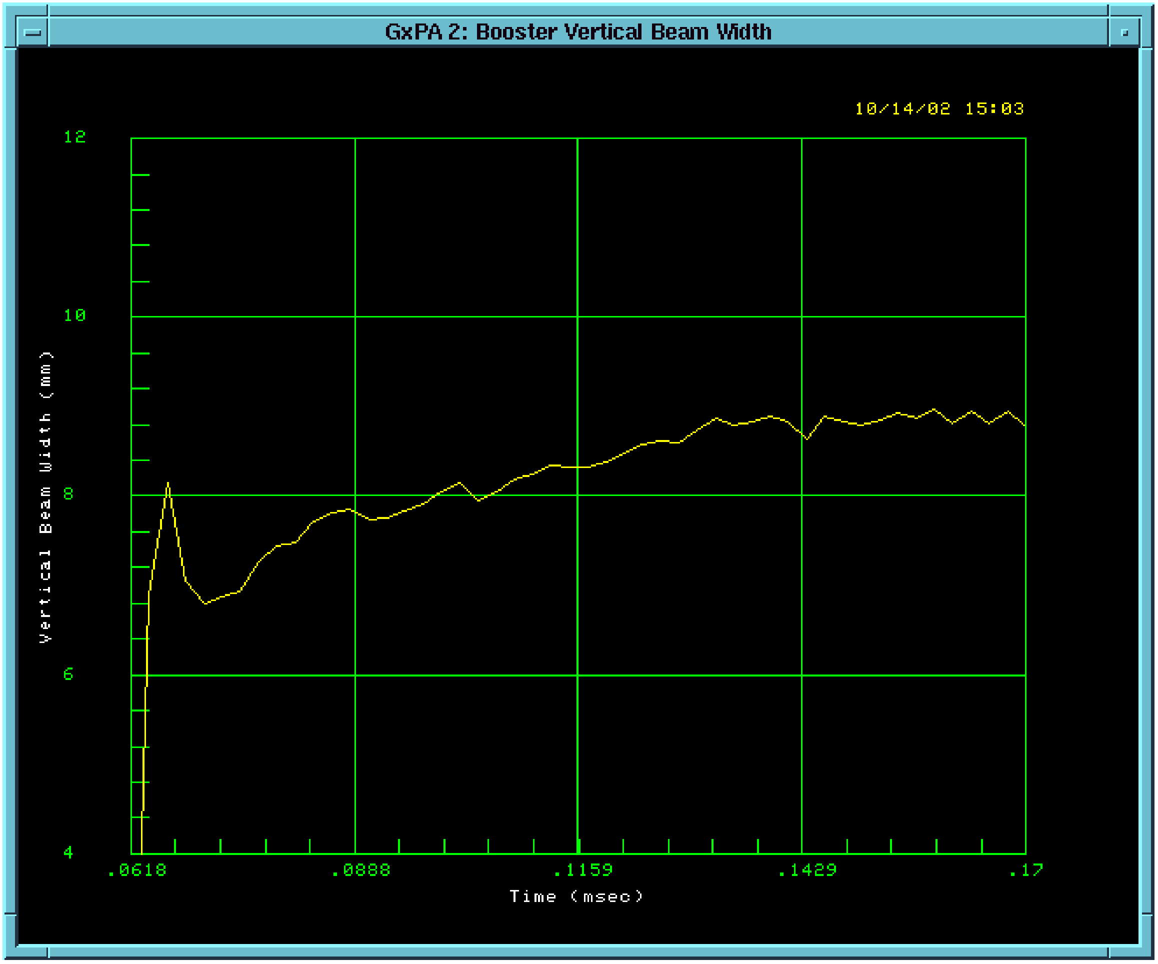


Author: Ray Tomlin
Date: October 14, 2002
Title: Booster bunch length near the transition

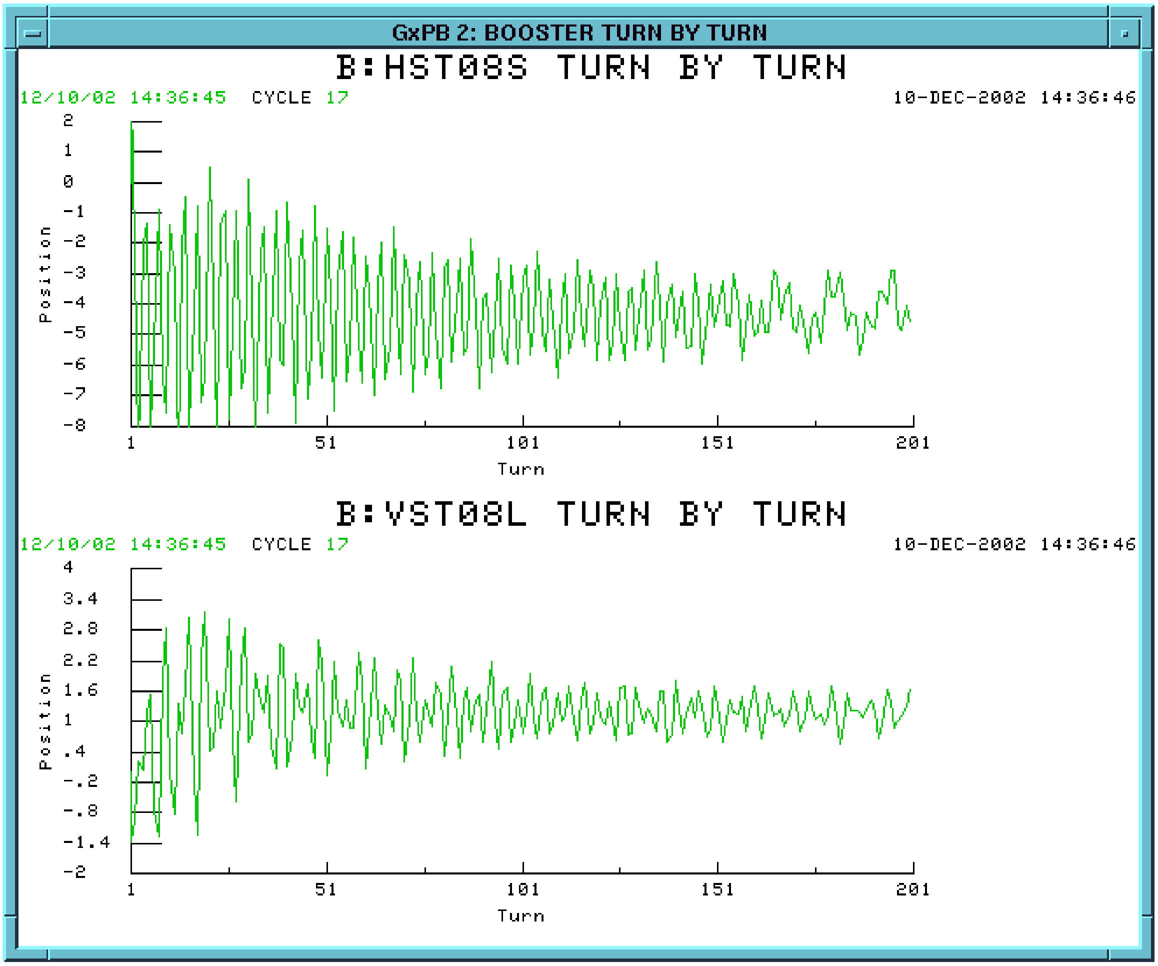


Author: Ray Tomlin
Date: October 14, 2002
Title: Booster beam width prior to the transition. IPM data. (The first turn injection is on the bottom of the horizontal data curve. There are 10 turns of injection.)

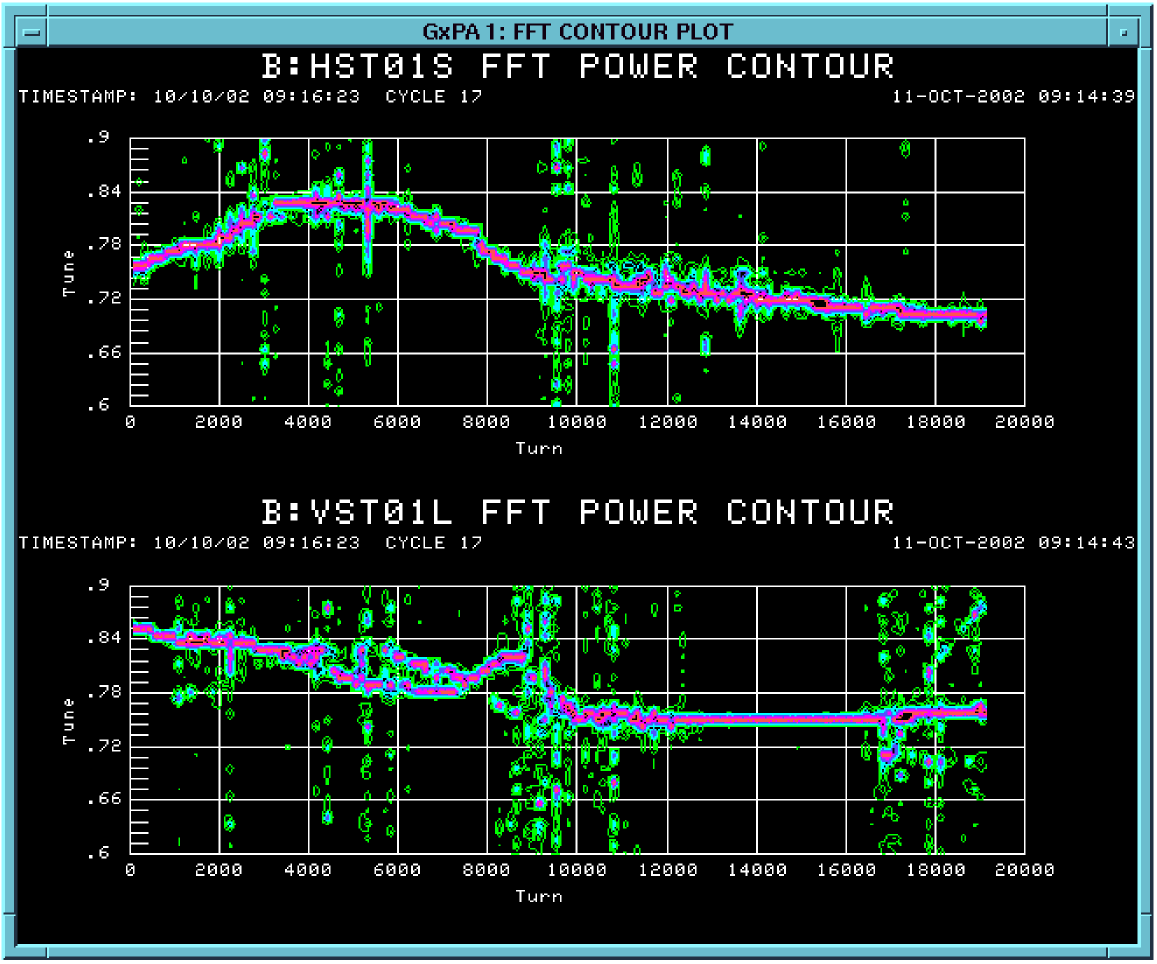



GxPA 2: Booster Vertical Beam Width
10/14/02 15:03
12
10
8
6
4
Vertical Beam Width (mm)
.0618
.0888
.1159
.1429
.17
Time (msec)

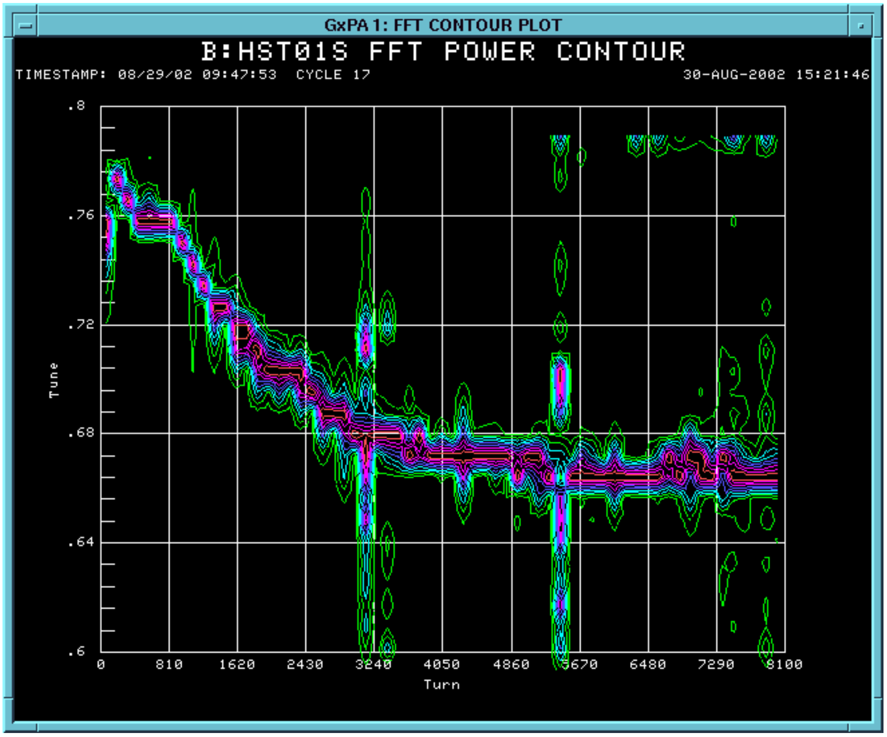
Author: Ray Tomlin
Date: December 10, 2002
Title: Injection painting by deliberately offsetting the injection point. (Horizontal painting reduces loss by about 20%. Vertical painting does not help probably due to aperture limit.)

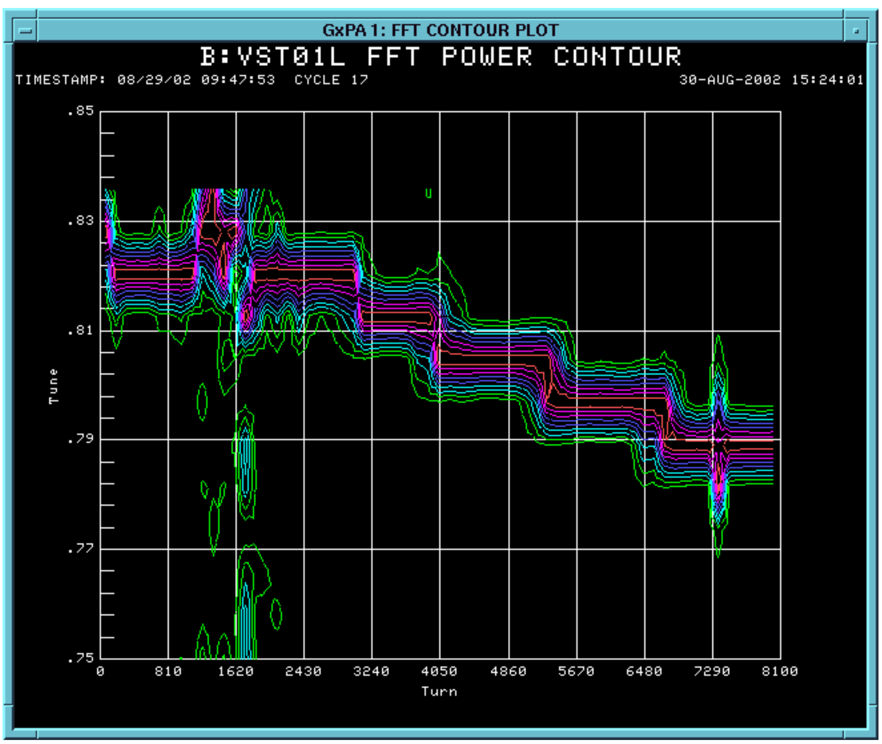


Author: Ray Tomlin
Date: October 11, 2002
Title: Booster tune throughout the cycle

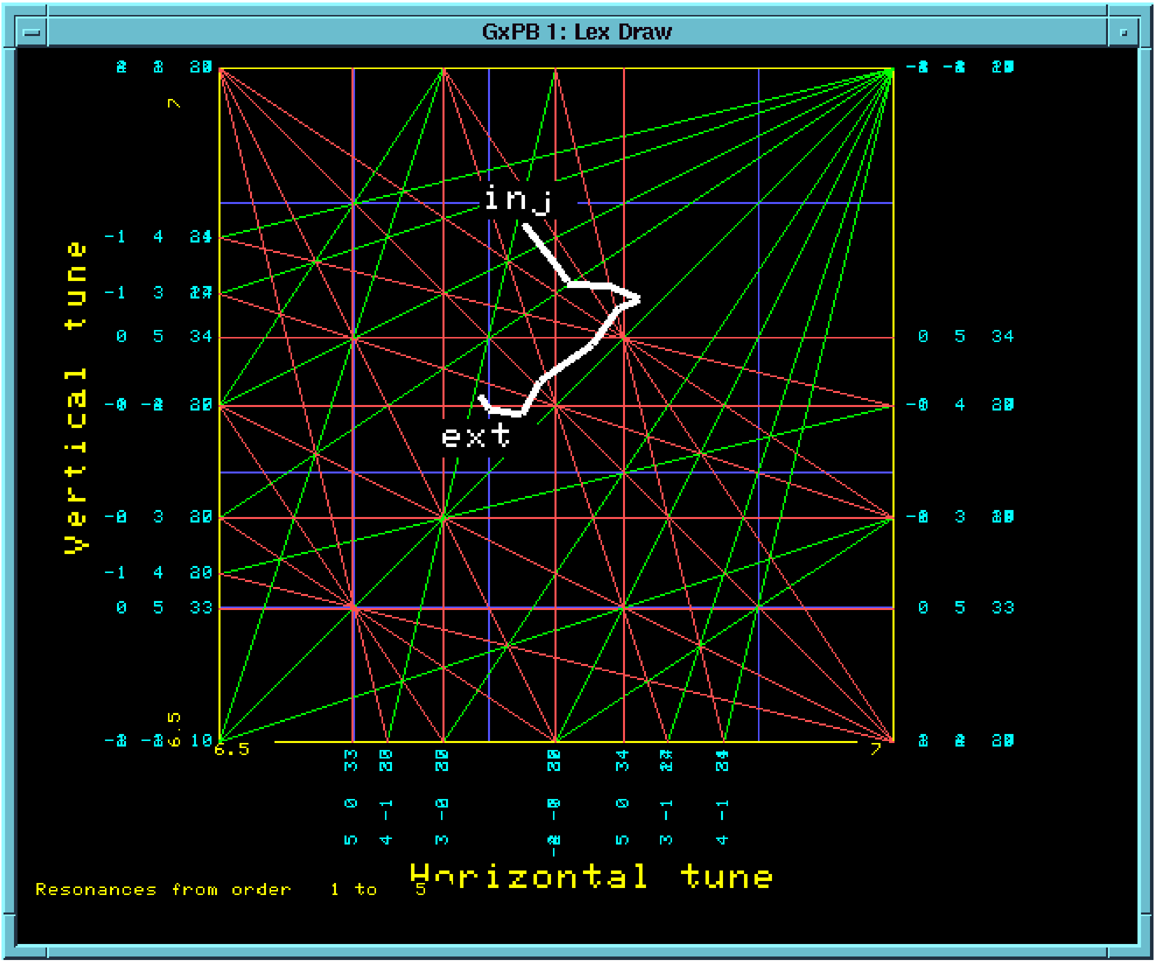


Author: Ray Tomlin
Date: August 30, 2002
Title: Booster bare tune throughout the cycle, all sextupoles OFF.

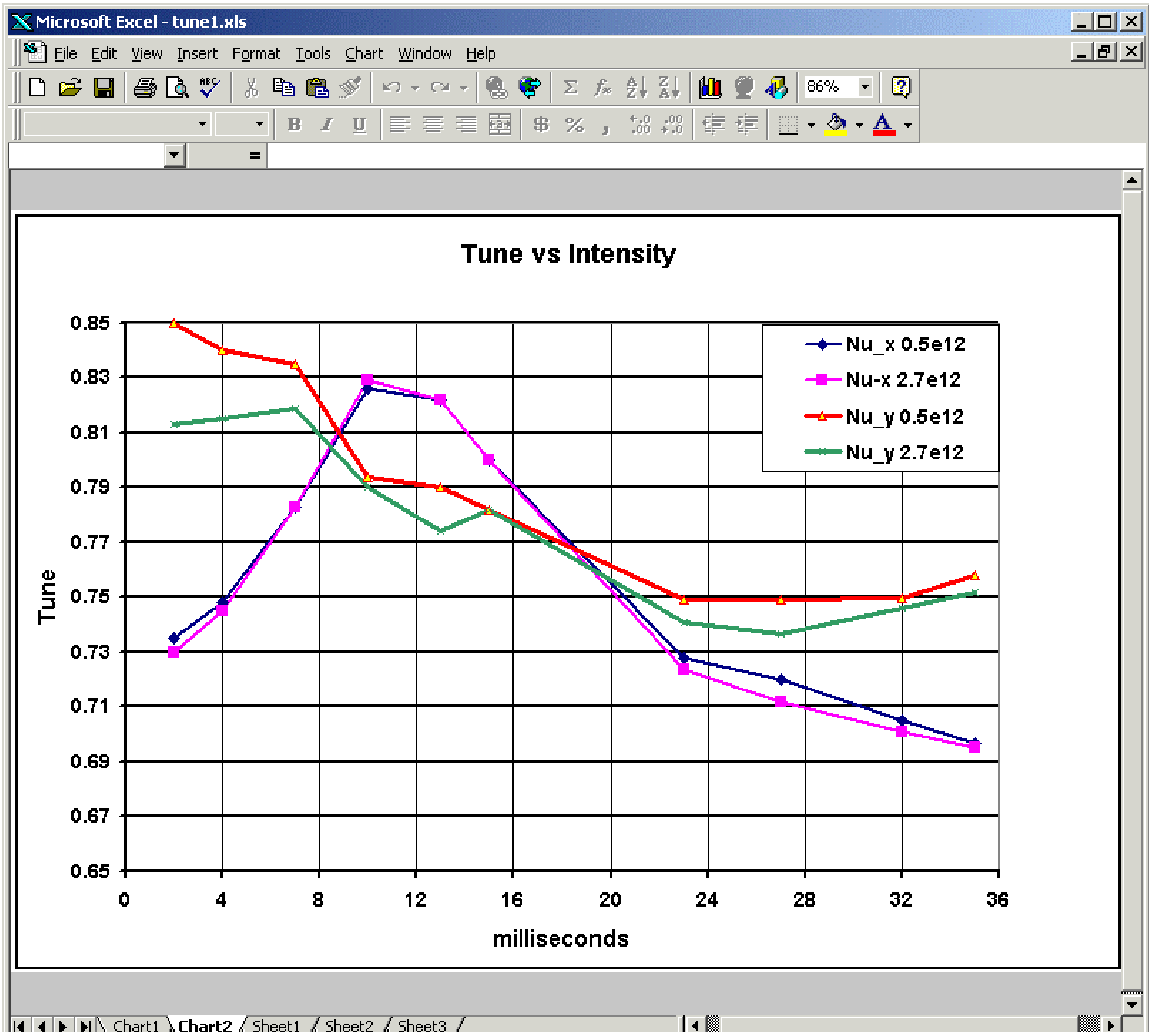




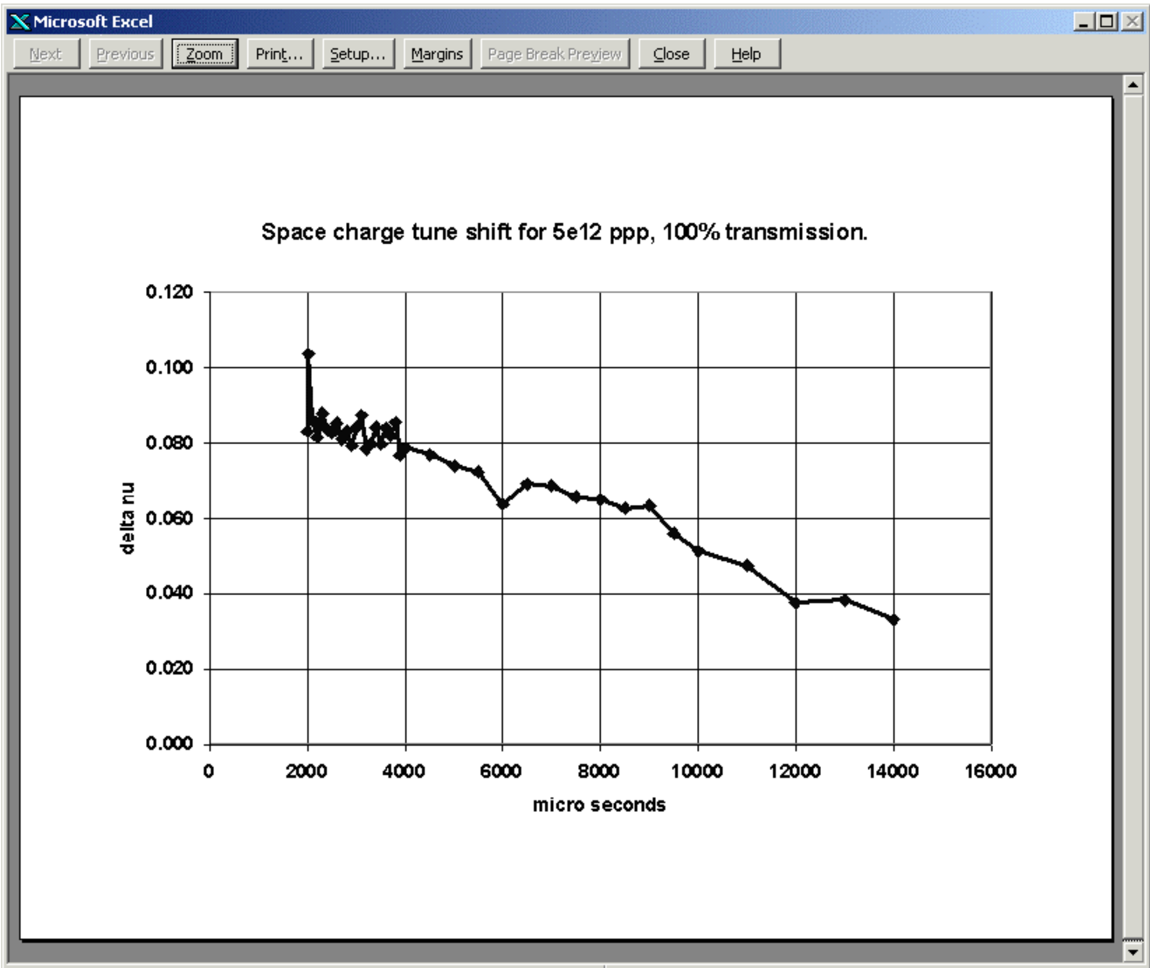
Author: Ray Tomlin
Date: October 9, 2002
Title: Booster tune diagram (tune path is for 1-turn injection, i.e., low intensity beam)

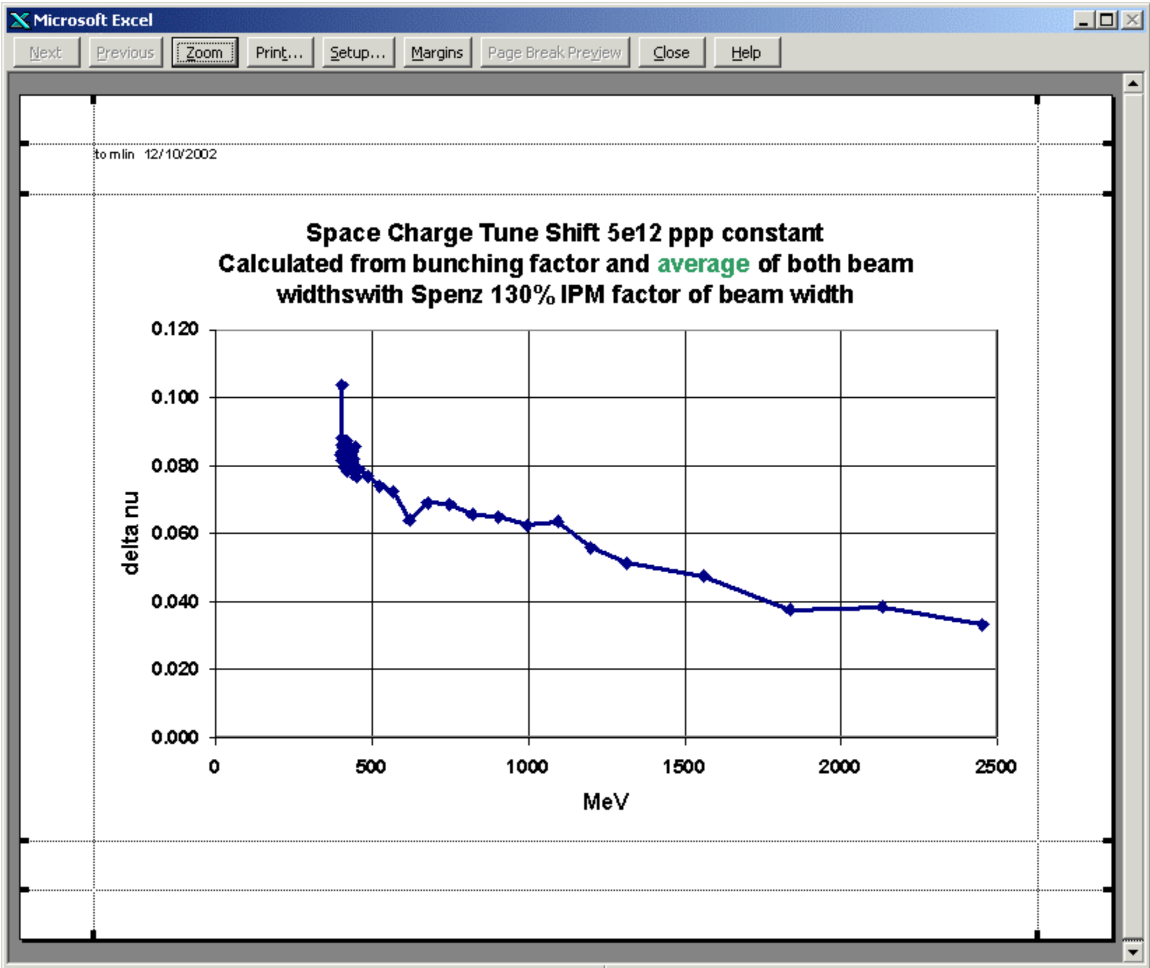


Author: Ray Tomlin
Date: Sept 30, 2002
Title: Booster tune shift with beam intensity throughout the cycle

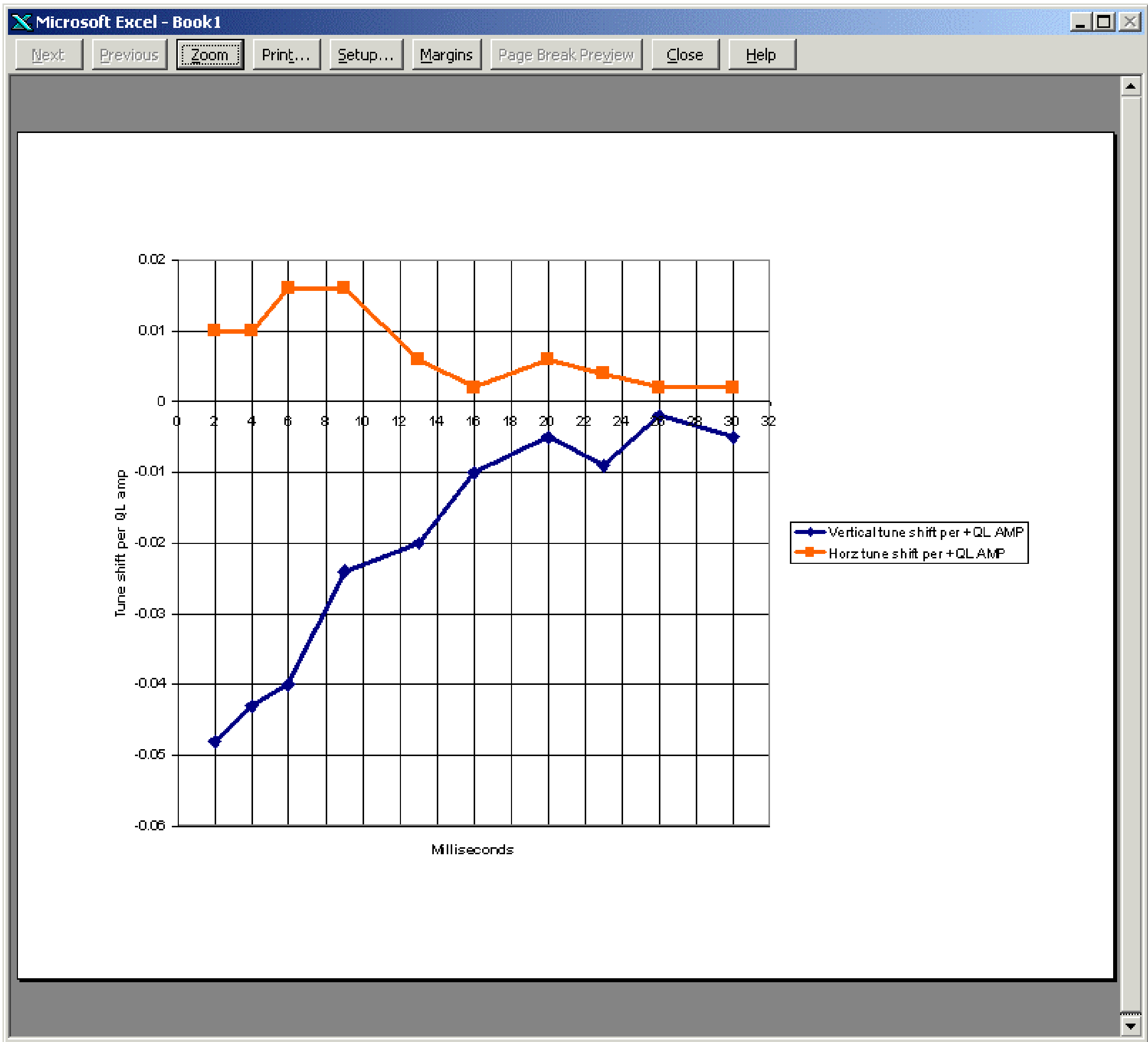


Author: Ray Tomlin
Date: December 10, 2002
Title: Booster tune shift with beam intensity throughout the cycle

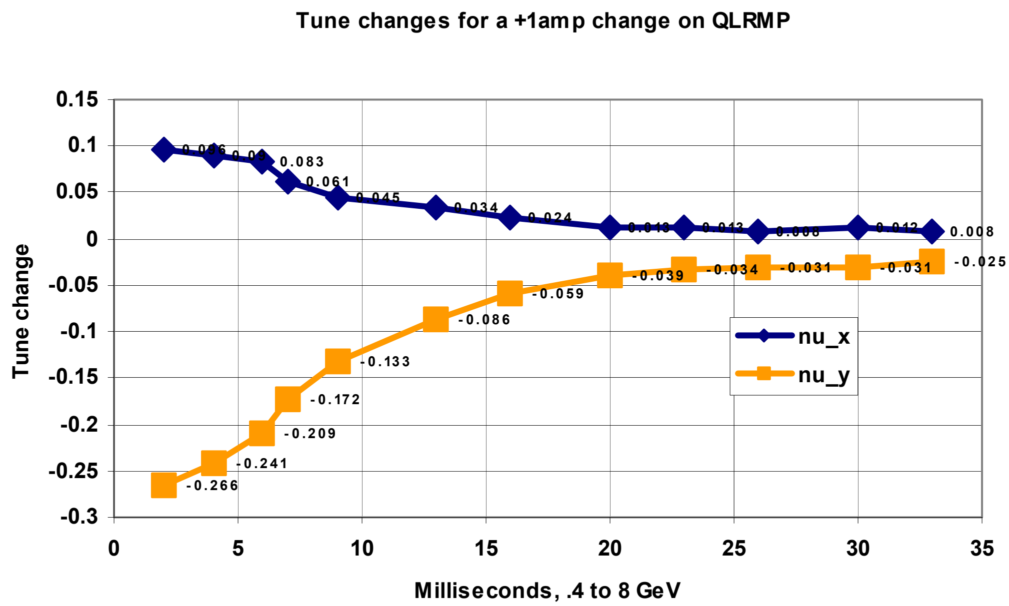


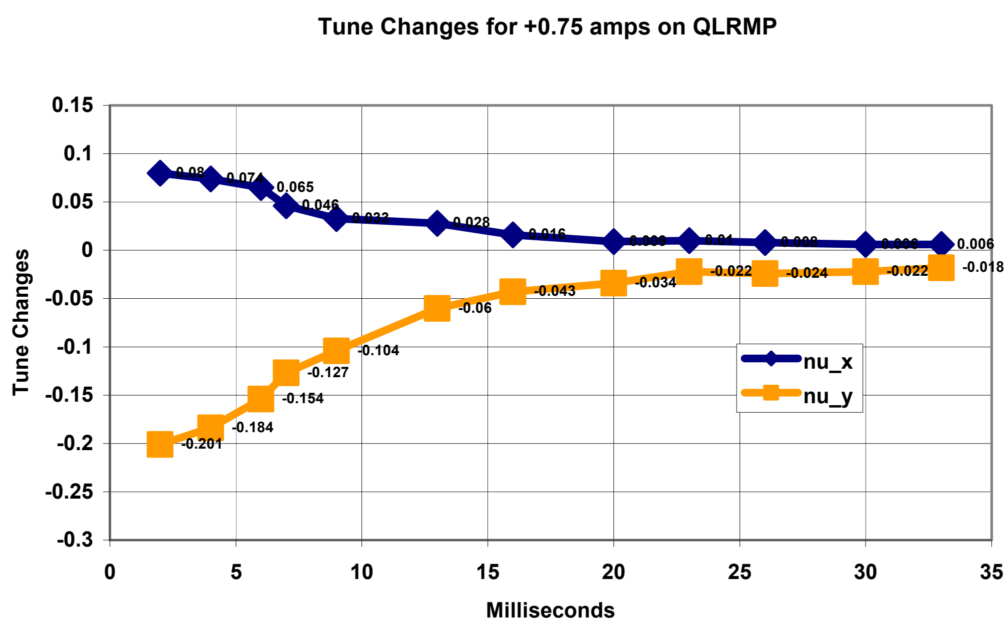

Microsoft Excel
Next
Previous
Zoom
Print...
Setup...
Margins
Page Break Preview
Close
Help
tomlin 12/10/2002
Space Charge Tune Shift 5e12 ppp constant
Calculated from bunching factor and average of both beam
widthswith Spenz 130% IPM factor of beam width
0.120
0.100
0.080
0.060
0.040
0.020
0.000
delta nu
0
500
1000
1500
2000
2500
MeV

Author: Ray Tomlin
Date: October 3, 2002
Title: Booster quadrupole tuning (tune shift per unit quad current)

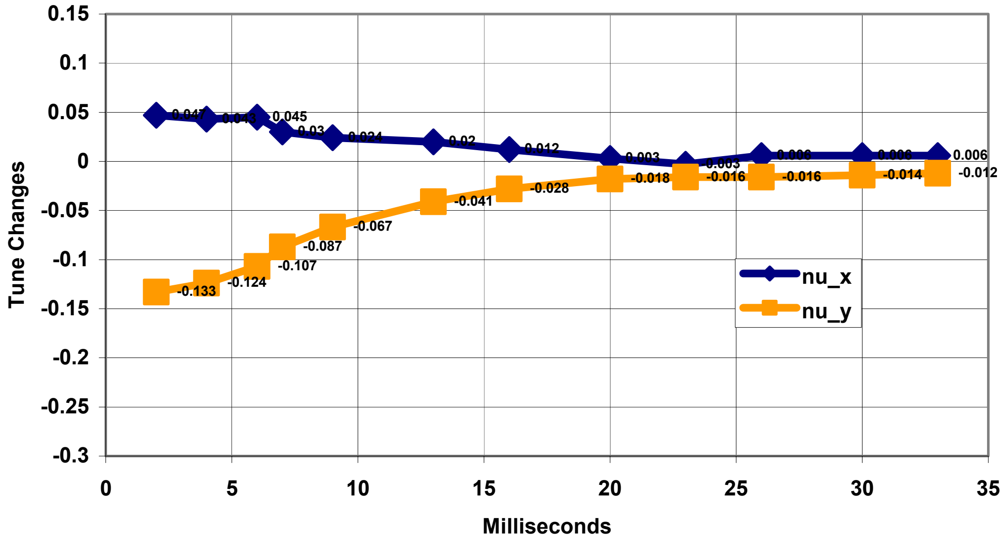


Author: Ray Tomlin
Date: October 14, 2002
Title: Booster quadrupole tuning (tune shift per unit quad current)

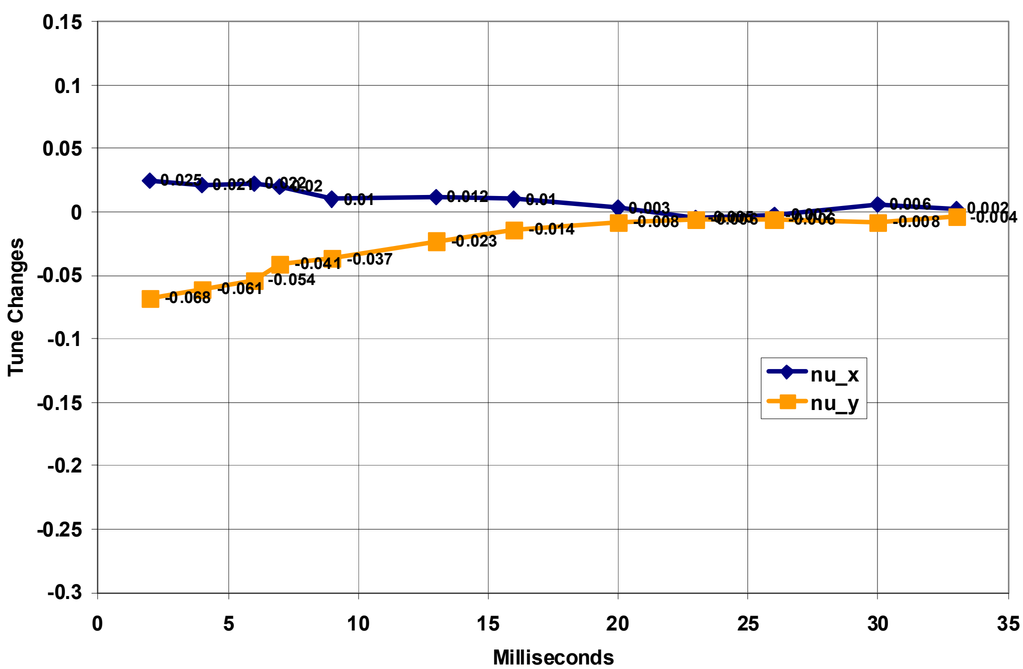




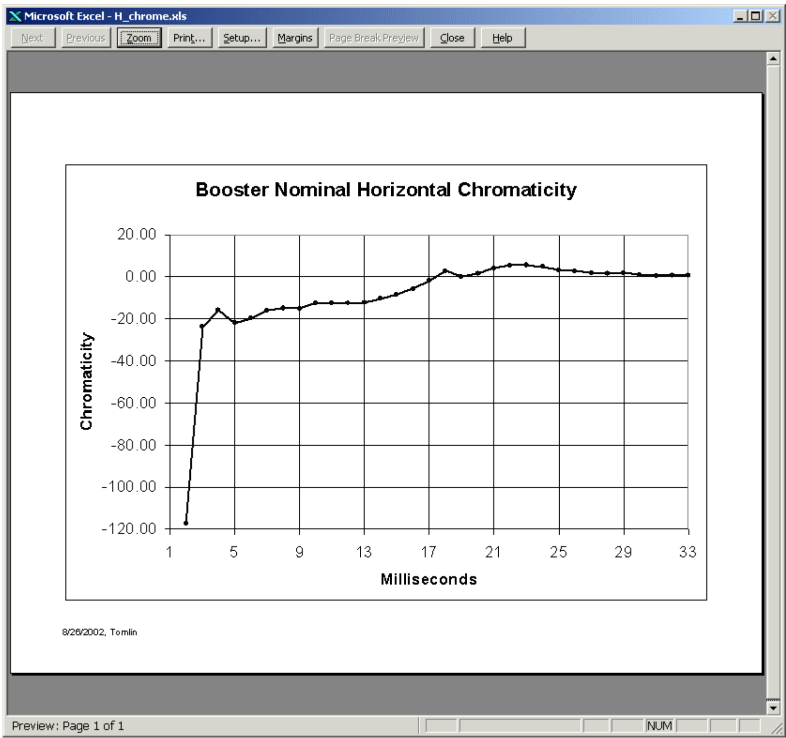
Tune Changes for +0.5 amps on QL

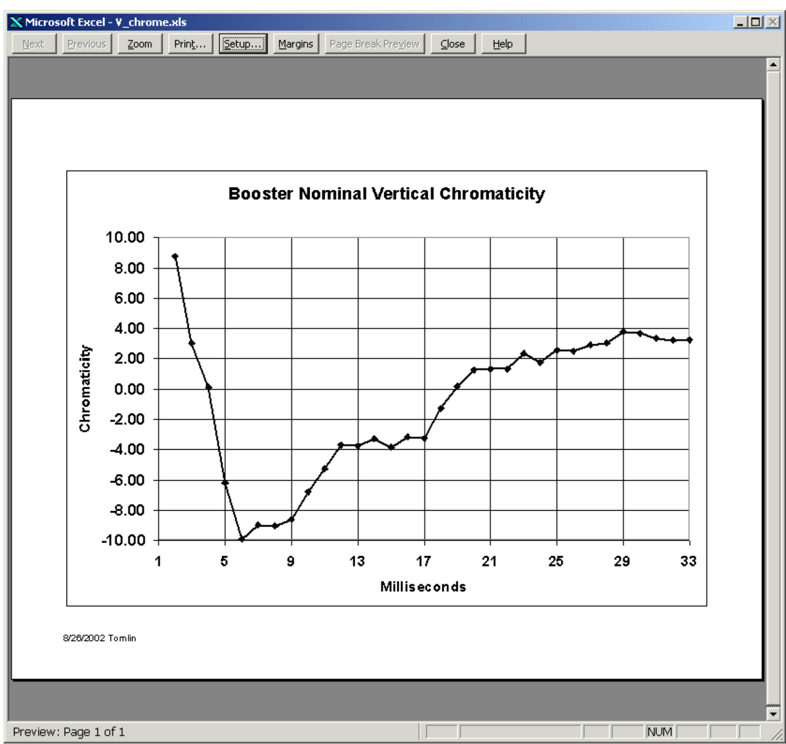


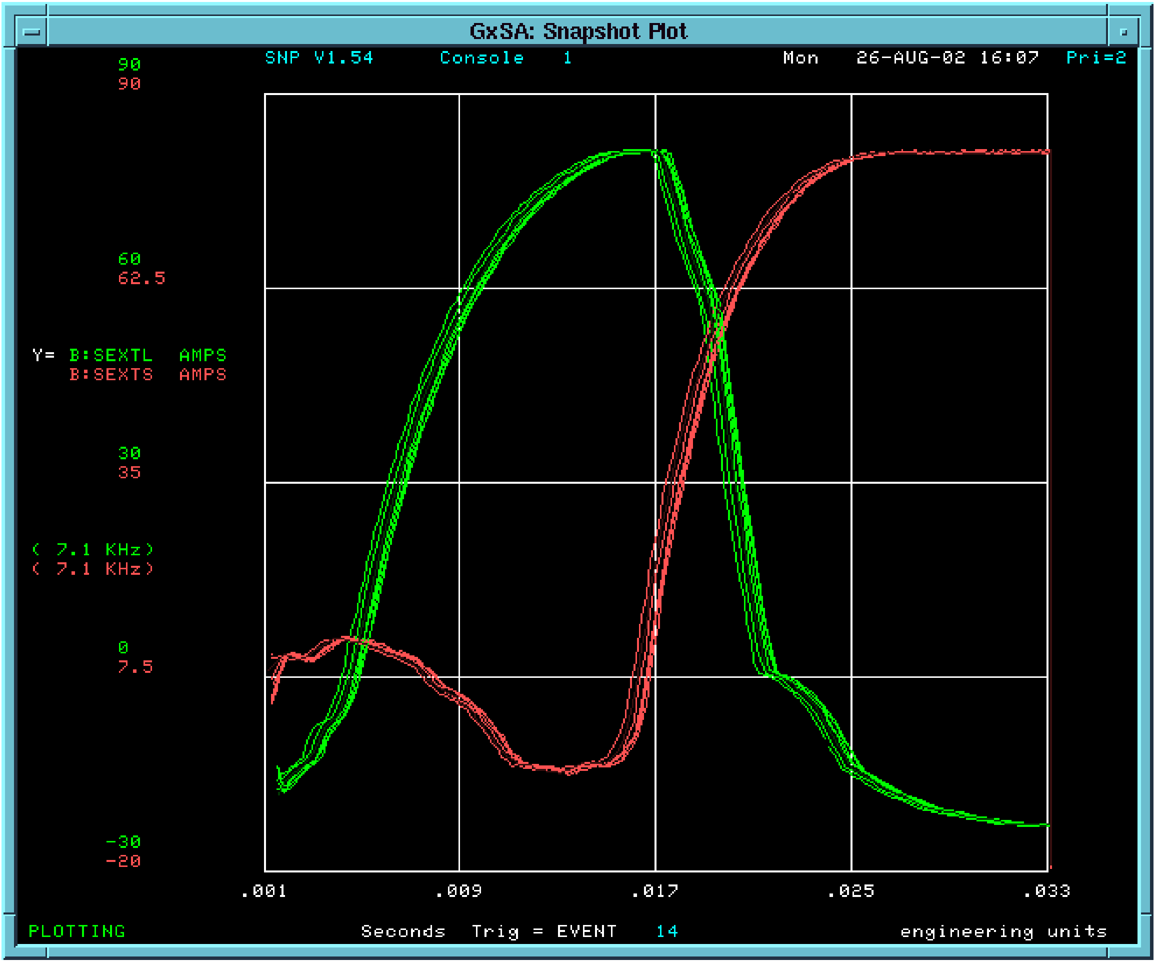
Tune Changes for +.25 amp on QL



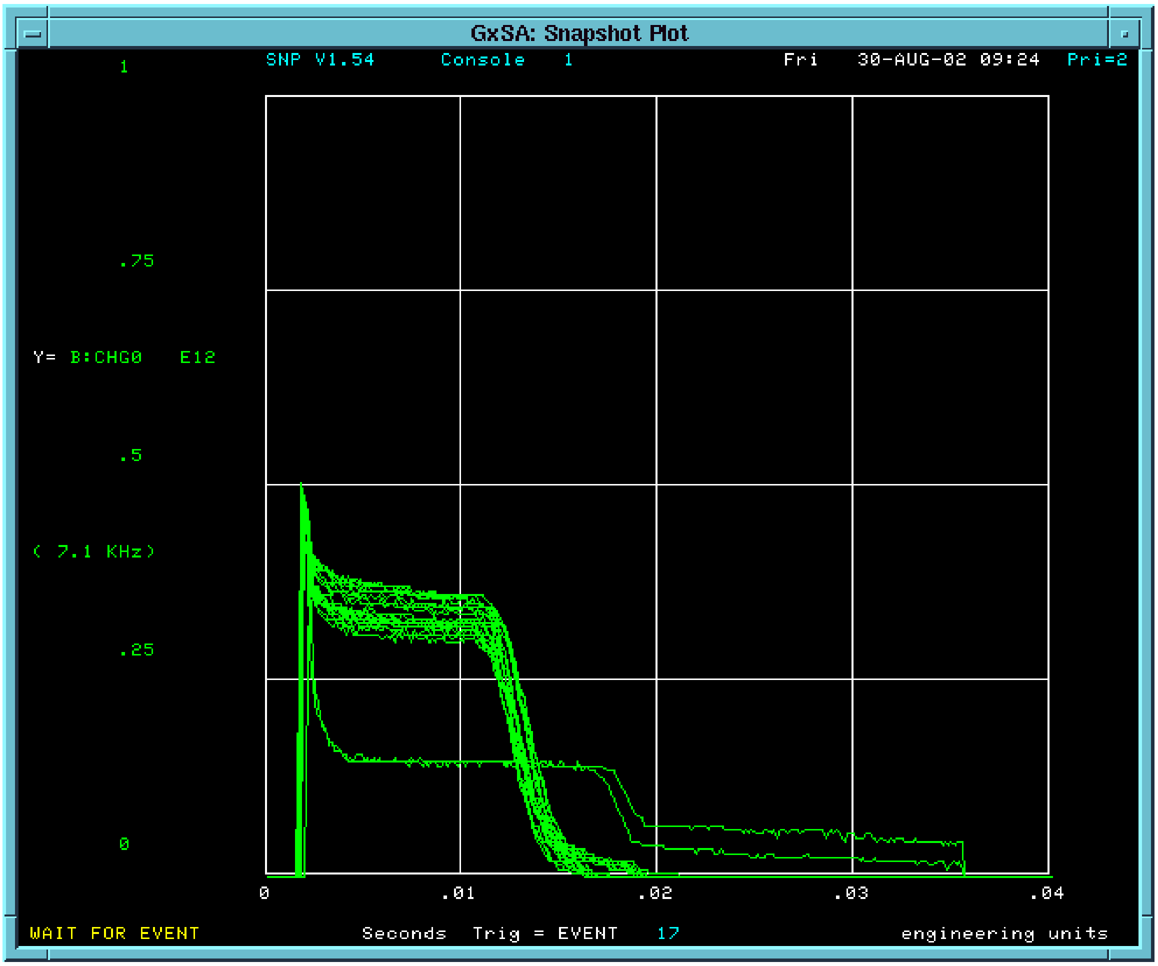
Author: Ray Tomlin
Date: August 26, 2002
Title: Booster chromaticity measurement and sextupole setting throughout the cycle. (The first data point in horizontal plane should be ignored.)

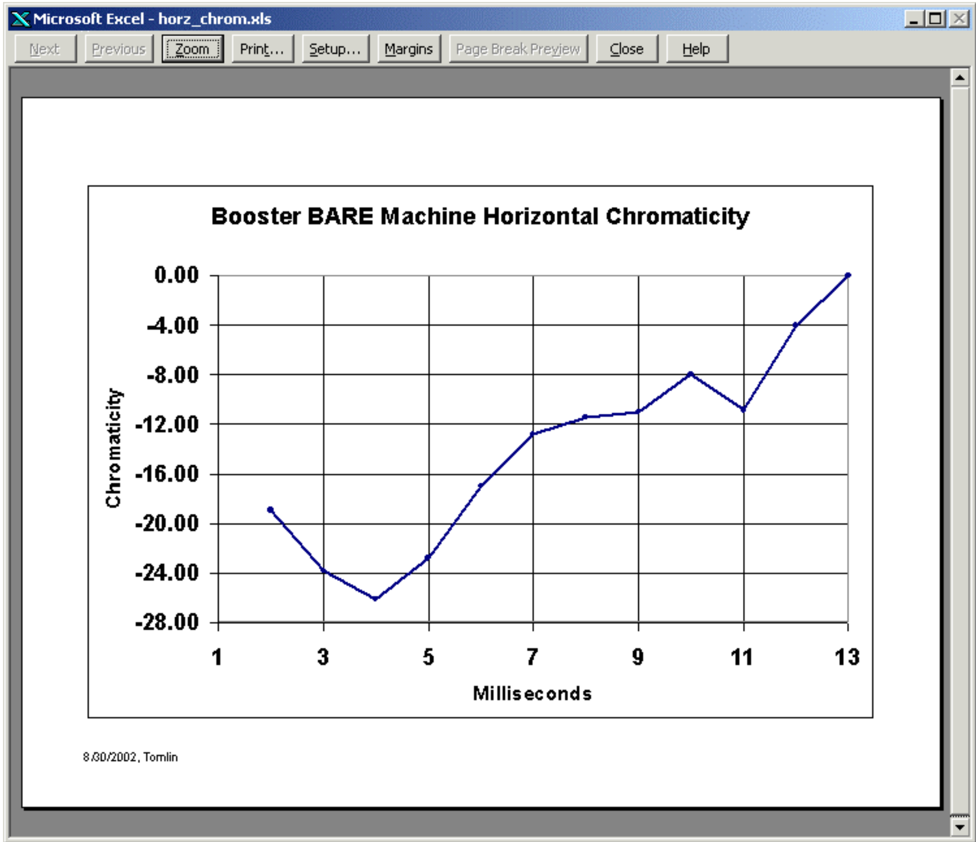


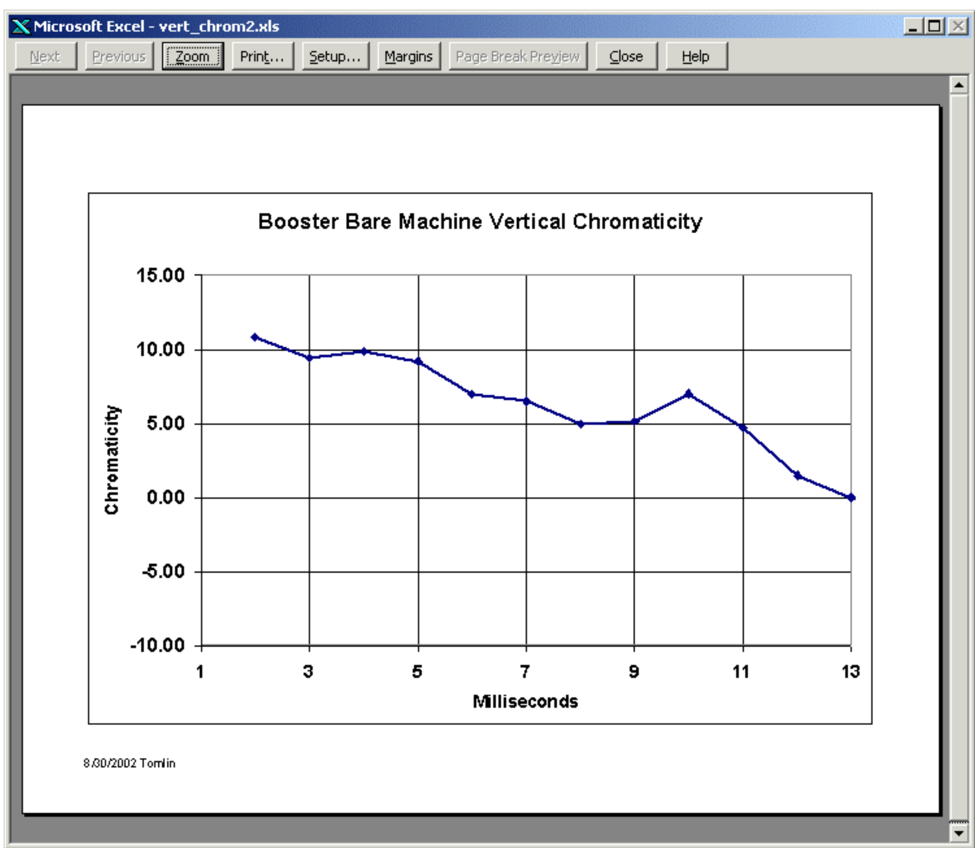



GxSA: Snapshot Plot
SNP V1.54 Console 1 Mon 26-AUG-02 16:07 Pri=2
90
90
60
62.5
Y= B:SEXTL AMPS
B:SEXTS AMPS
30
35
(7.1 KHz)
(7.1 KHz)
0
7.5
-30
-20
.001 .009 .017 .025 .033
PLOTTING Seconds Trig = EVENT 14 engineering units

Author: Ray Tomlin
Date: January10, 2002
Title: Booster chromaticity measurement with all sextupoles OFF. (Beam cannot survive beyond 13 ms.)




Microsoft Excel - horz_chrom.xls
Next
Previous
Zoom
Print...
Setup...
Margins
Page Break Preview
Close
Help
Booster BARE Machine Horizontal Chromaticity
0.00
-4.00
-8.00
-12.00
-16.00
-20.00
-24.00
-28.00
Chromaticity
1
3
5
7
9
11
13
Milliseconds
8/30/2002, Tomlin

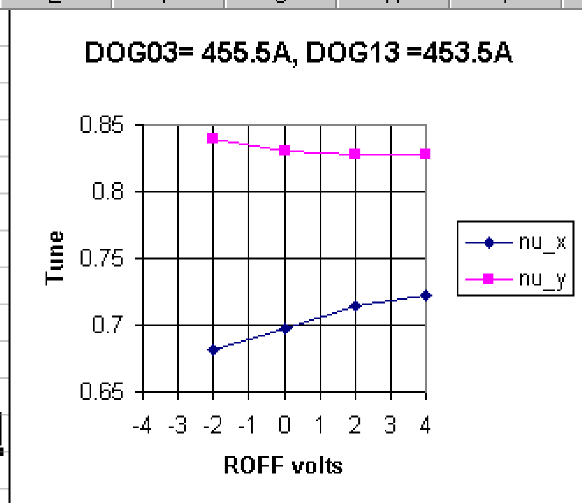

Microsoft Excel - vert_chrom2.xls
Next
Previous
Zoom
Print...
Setup...
Margins
Page Break Preview
Close
Help
Booster Bare Machine Vertical Chromaticity
15.00
10.00
5.00
0.00
-5.00
-10.00
Chromaticity
1
3
5
7
9
11
13
Milliseconds
8/30/2002 Tomlin

Author: Ray Tomlin
Date: January10, 2002
Title: Booster chromaticity measurement at injection, with all sextupoles OFF. (It is seen that the dogleg effect is small - No apparent change in chromaticity when the dogleg current is changed by 200 A.)

Microsoft Excel - dogSex.xls

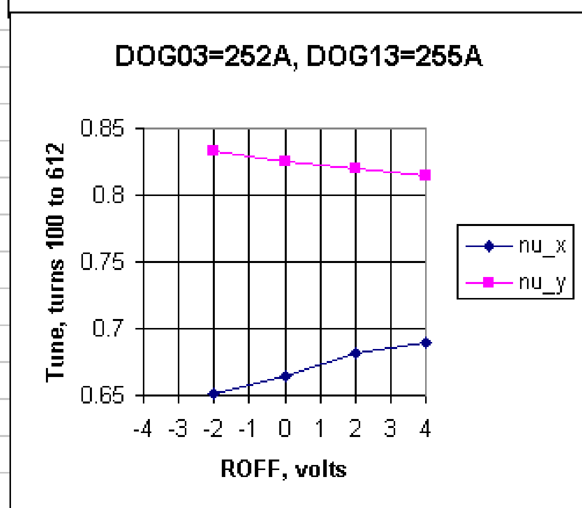
dp/p%	ROFF	nu_x	nu_y
0.0745	-2	0.681	0.84
	0	0.697	0.83
	2	0.715	0.828
0.0671	4	0.723	0.828

DOG03=455.5A
DOG13=453.5A



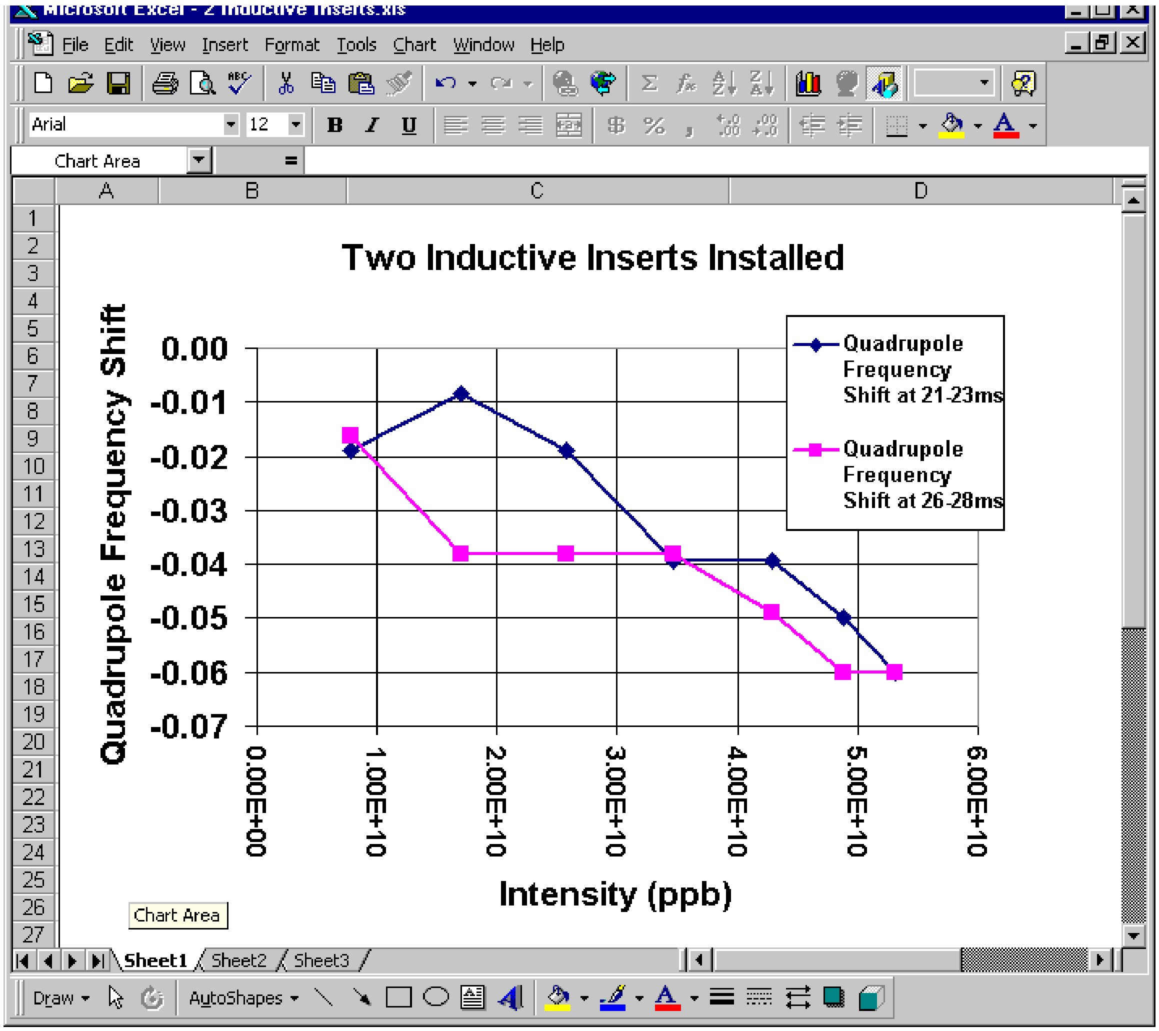
DOG03=252 A
DOG03=255 A

dp/p%	ROFF	nu_x	nu_y
0.0745	-2	0.651	0.833
	0	0.664	0.825
	2	0.682	0.82
0.0671	4	0.69	0.815

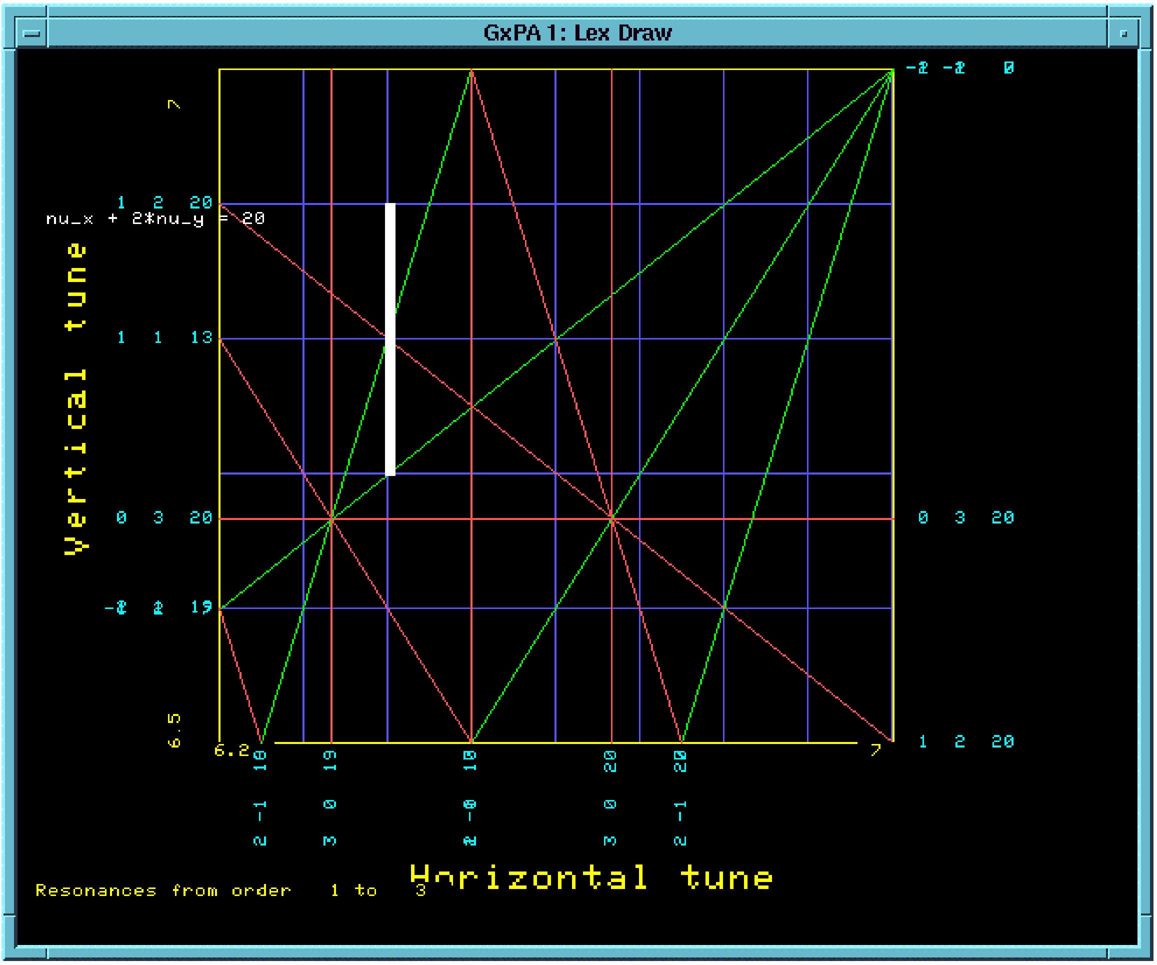


Vertical chromaticity increases 28% (less negative) for 100 amps increase on both DOGs
Horizontal chromaticity decreases 25% (less positive) for 100 amps increase on both DOGs
Vertical tune goes +0.006 for a 100 amp increase on both DOGs
Horizontal tune goes +0.0154 for a 100 amp increase on both DOGs

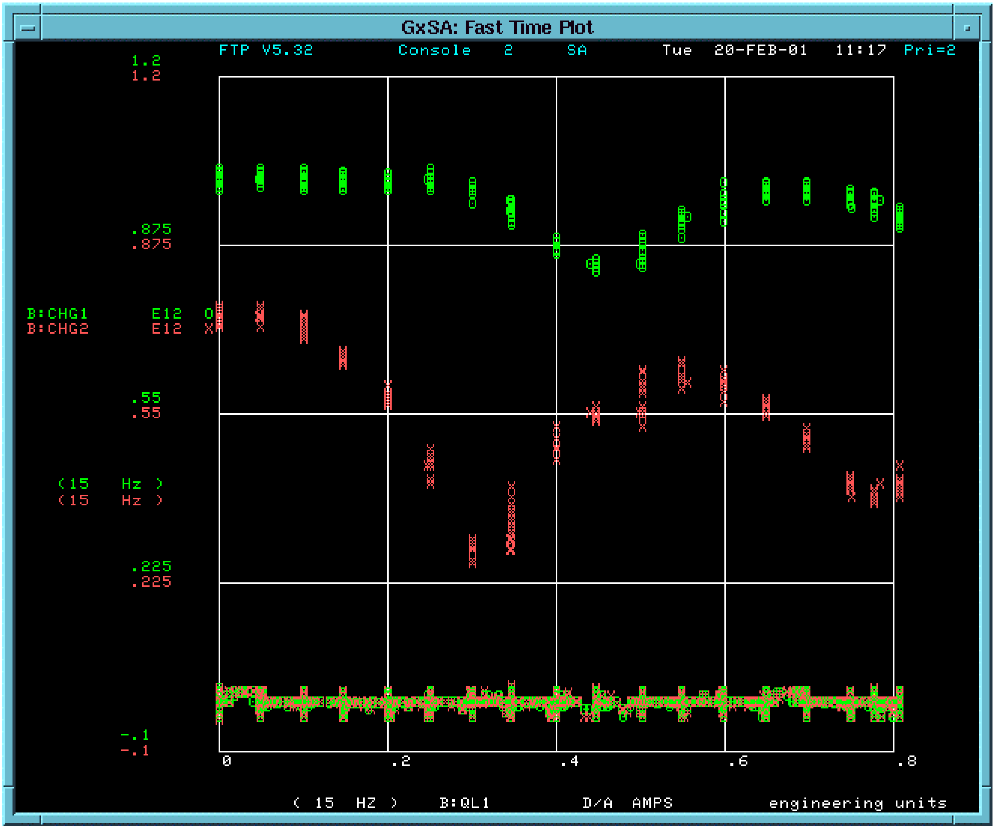
Author: Ray Tomlin
Date: May 31, 2002
Title: Booster beam longitudinal quadrupole frequency shift as a function of beam intensity. (Two inductive insert modules are in place.)

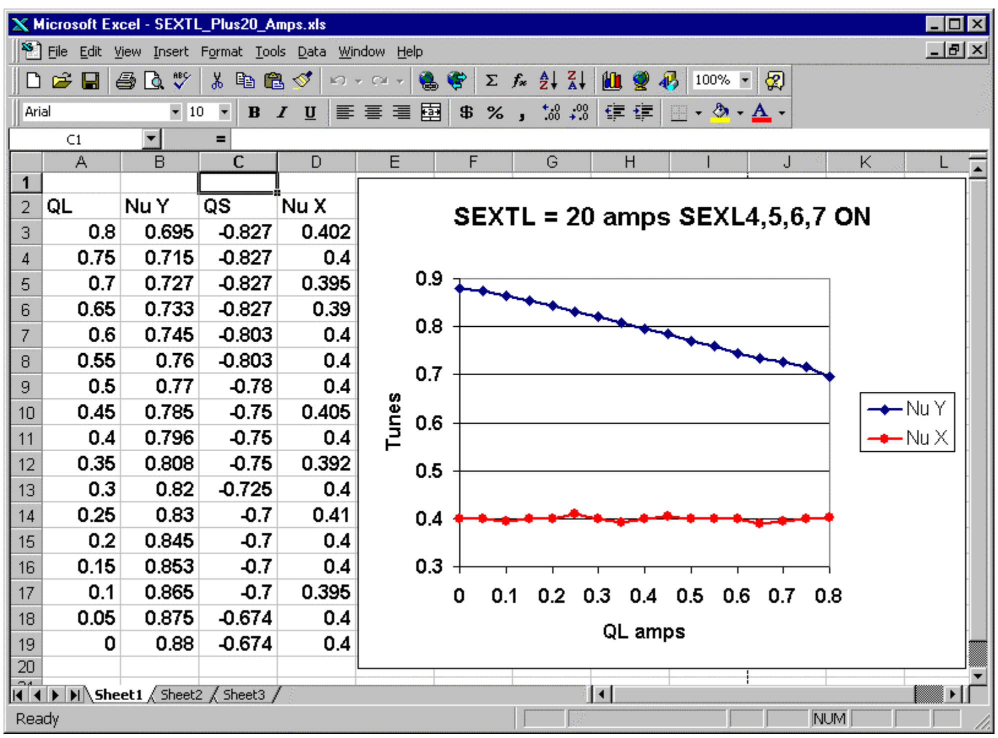


Author: Ray Tomlin, Chuck Ankenbrandt
Date: February 20, 2001
Title: Booster stopband nu_x + 2*nu_y = 20 measurement



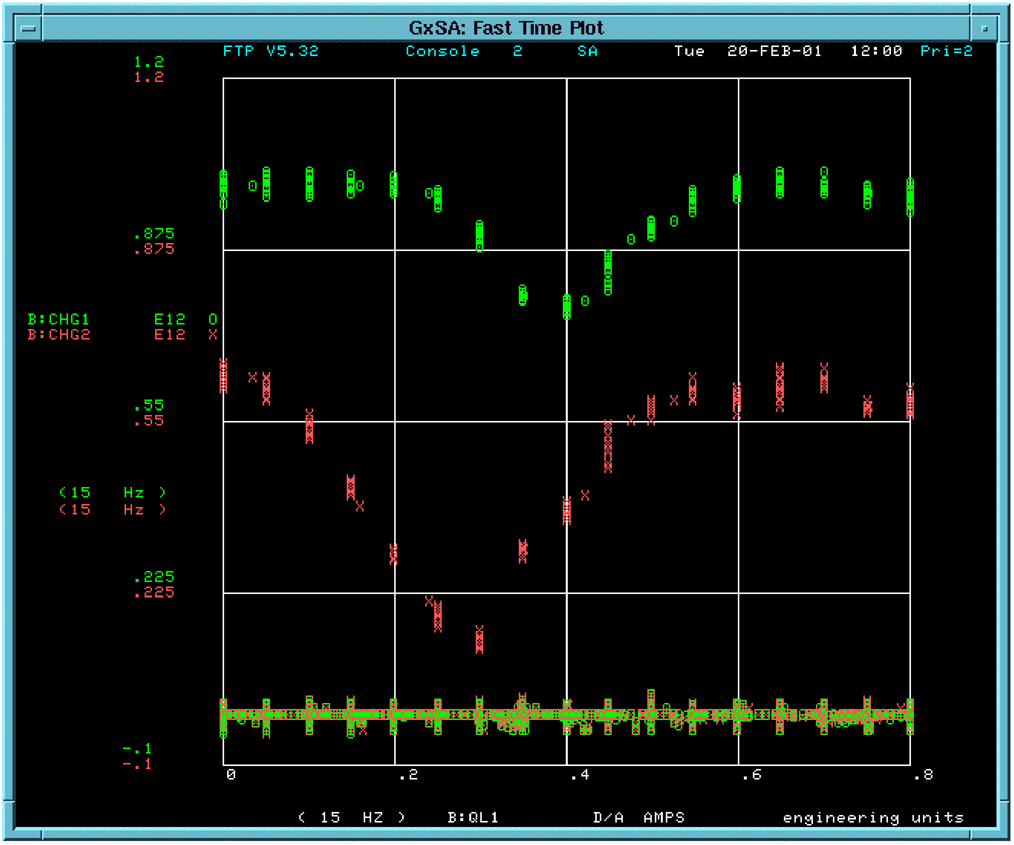
Measurement No. 1: SEXTL = + 20 A, SEXL 4,5,6,7 on



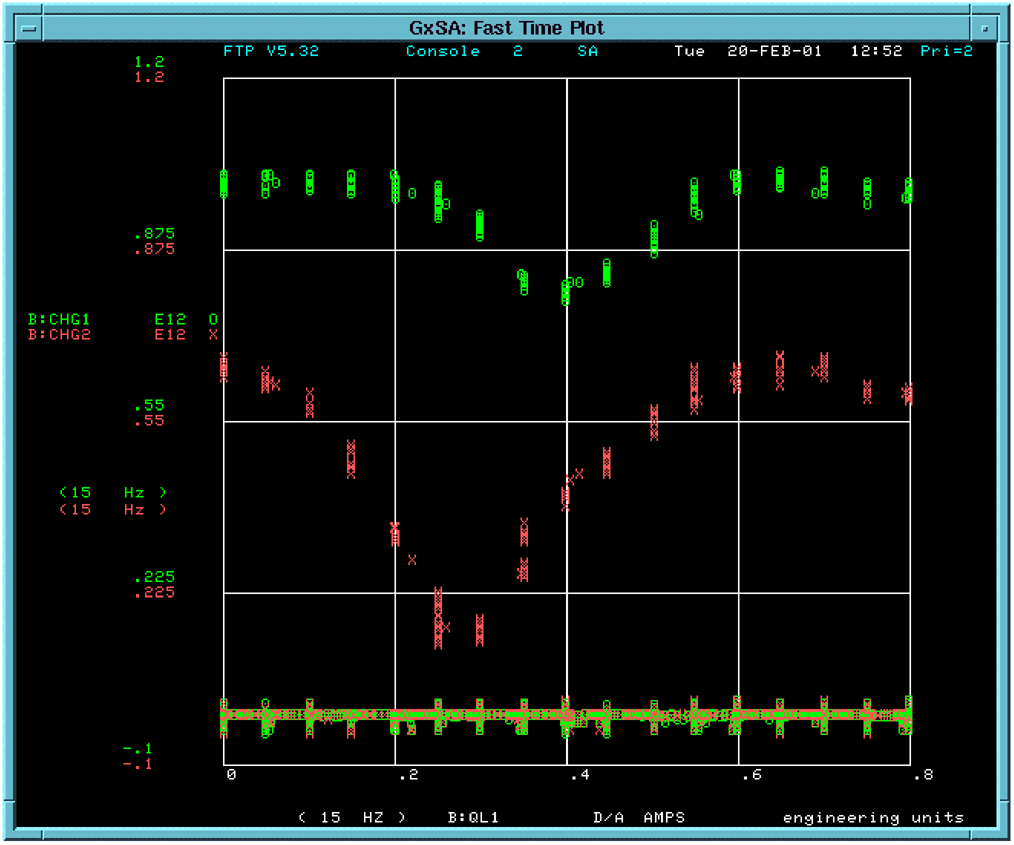


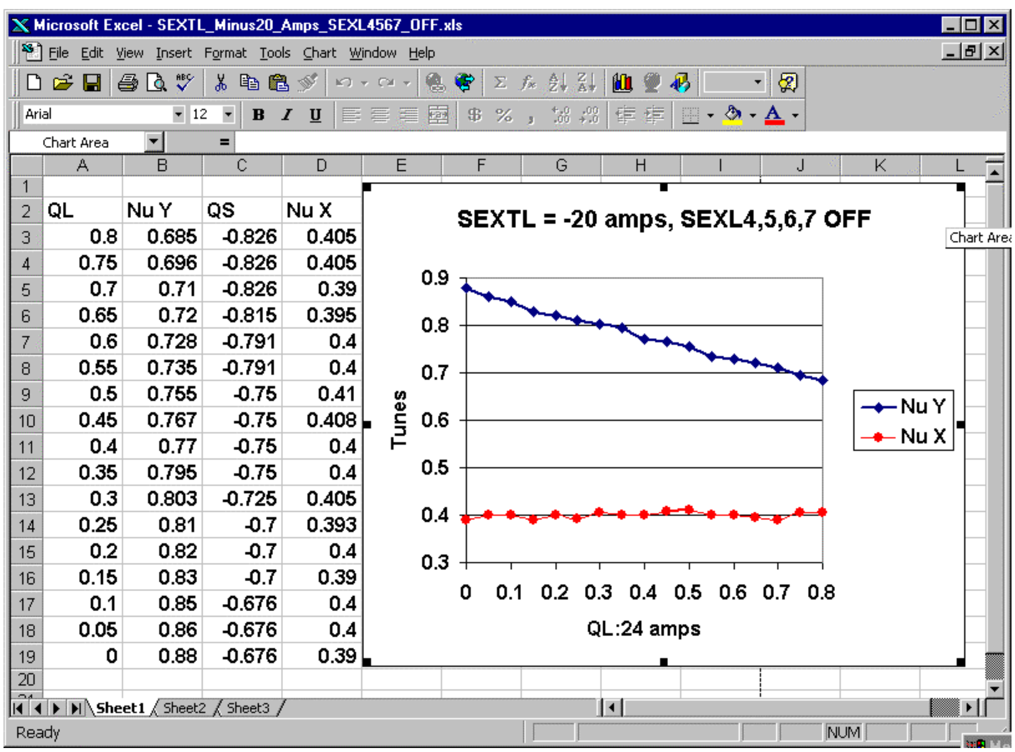
QL	Nu Y	QS	Nu X
0.8	0.695	-0.827	0.402
0.75	0.715	-0.827	0.4
0.7	0.727	-0.827	0.395
0.65	0.733	-0.827	0.39
0.6	0.745	-0.803	0.4
0.55	0.76	-0.803	0.4
0.5	0.77	-0.78	0.4
0.45	0.785	-0.75	0.405
0.4	0.796	-0.75	0.4
0.35	0.808	-0.75	0.392
0.3	0.82	-0.725	0.4
0.25	0.83	-0.7	0.41
0.2	0.845	-0.7	0.4
0.15	0.853	-0.7	0.4
0.1	0.865	-0.7	0.395
0.05	0.875	-0.674	0.4
0	0.88	-0.674	0.4

Measurement No. 2: SEXTL = - 20 A, SEXL 4,5,6,7 on:



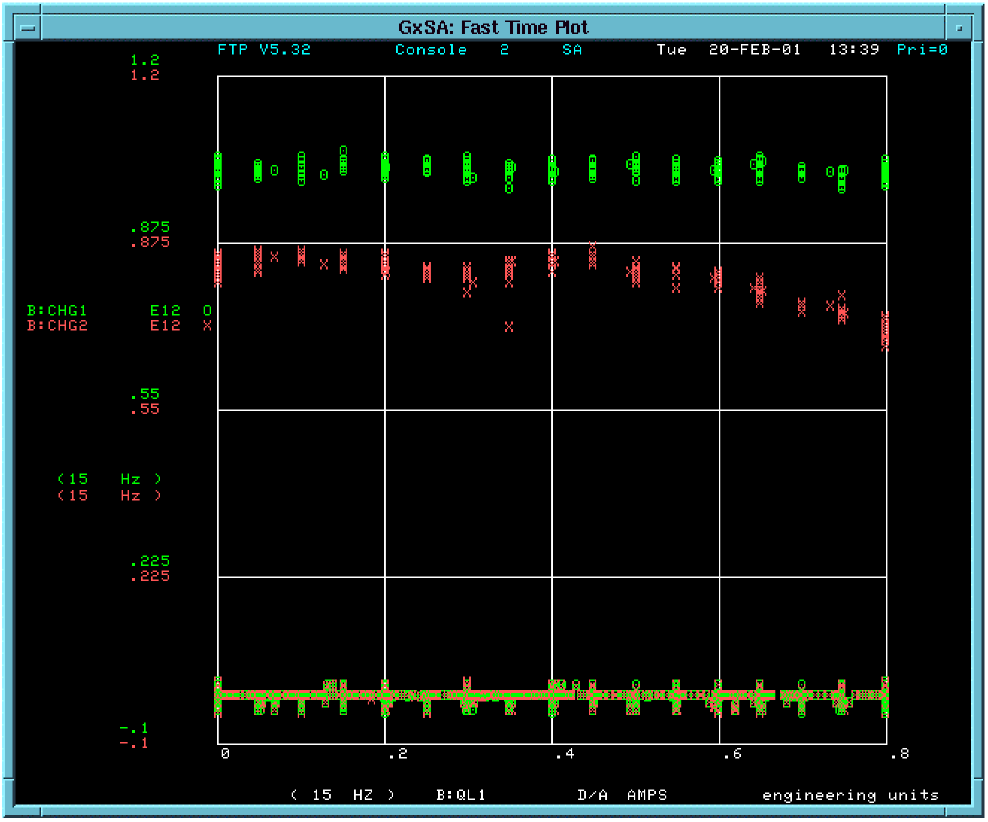
Measurement No. 3: SEXTL = - 20 A, SEXL 4,5,6,7 off

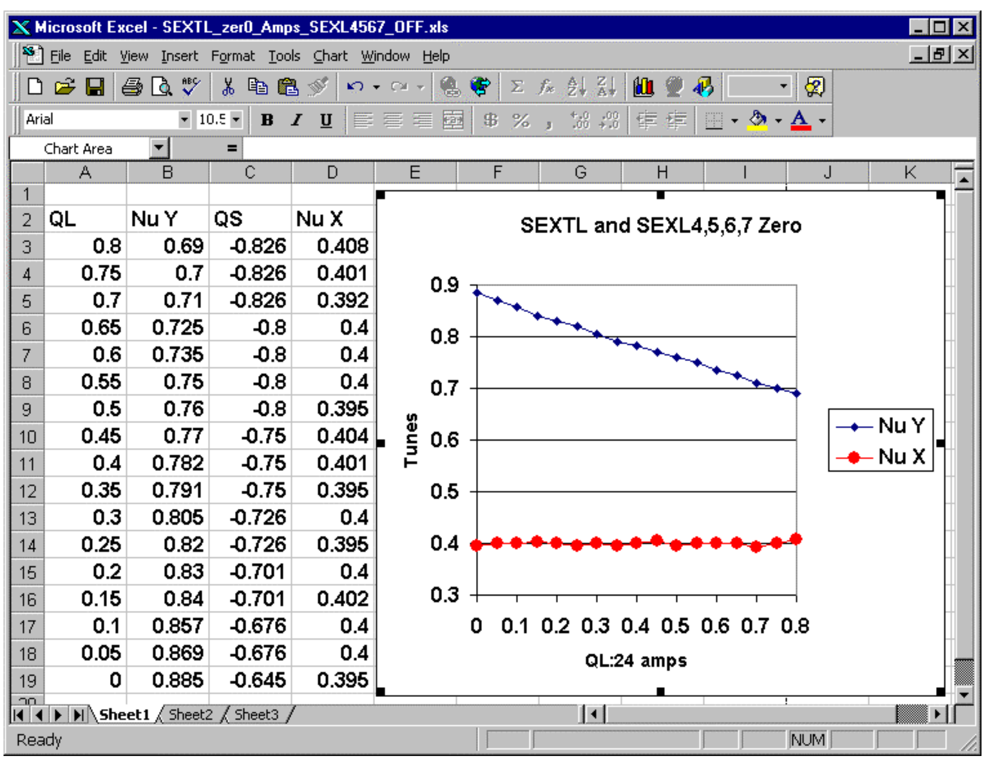




QL	Nu Y	QS	Nu X
0.8	0.685	-0.826	0.405
0.75	0.696	-0.826	0.405
0.7	0.71	-0.826	0.39
0.65	0.72	-0.815	0.395
0.6	0.728	-0.791	0.4
0.55	0.735	-0.791	0.4
0.5	0.755	-0.75	0.41
0.45	0.767	-0.75	0.408
0.4	0.77	-0.75	0.4
0.35	0.795	-0.75	0.4
0.3	0.803	-0.725	0.405
0.25	0.81	-0.7	0.393
0.2	0.82	-0.7	0.4
0.15	0.83	-0.7	0.39
0.1	0.85	-0.676	0.4
0.05	0.86	-0.676	0.4
0	0.88	-0.676	0.39

Measurement No. 4: SEXTL = 0 A, SEXL 4,5,6,7 off





QL	Nu Y	QS	Nu X
0.8	0.69	-0.826	0.408
0.75	0.7	-0.826	0.401
0.7	0.71	-0.826	0.392
0.65	0.725	-0.8	0.4
0.6	0.735	-0.8	0.4
0.55	0.75	-0.8	0.4
0.5	0.76	-0.8	0.395
0.45	0.77	-0.75	0.404
0.4	0.782	-0.75	0.401
0.35	0.791	-0.75	0.395
0.3	0.805	-0.726	0.4
0.25	0.82	-0.726	0.395
0.2	0.83	-0.701	0.4
0.15	0.84	-0.701	0.402
0.1	0.857	-0.676	0.4
0.05	0.869	-0.676	0.4
0	0.885	-0.645	0.395